Modeling Hadronization Measurements

Will Brooks
Universidad Técnica Federico Santa María
Valparaíso, Chile

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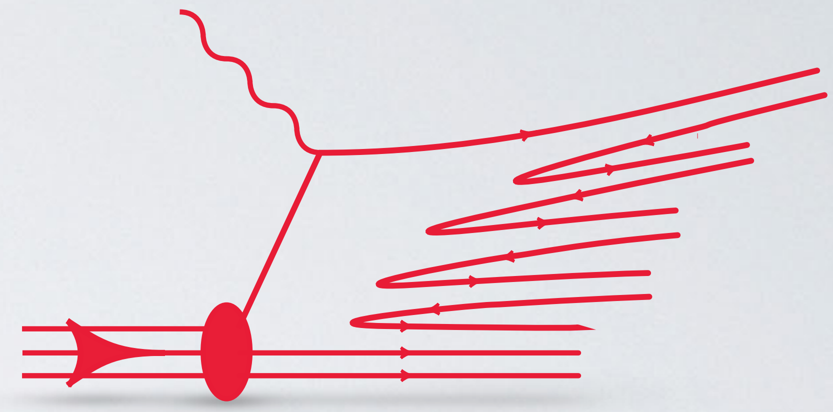
Outline

- Brief introduction
- Exploring a direct measurement of quark energy loss
- Production length extraction: results of feasibility study
- Conclusions

Overarching Goals

- Understand the fundamental dynamics of color propagation and neutralization (in the vacuum)
  - ➡ Characteristic times
  - ➡ Hadronization mechanisms (mesons, baryons)
- Understand parton-level interactions with nuclear medium
  - ➡ Transport coefficients:
    - ➡ $\hat{q}$ (p_T broadening)
    - ➡ $\hat{e}$ (longitudinal energy loss)
  - ➡ Polarization (future)

FUNDAMENTAL QCD PROCESSES

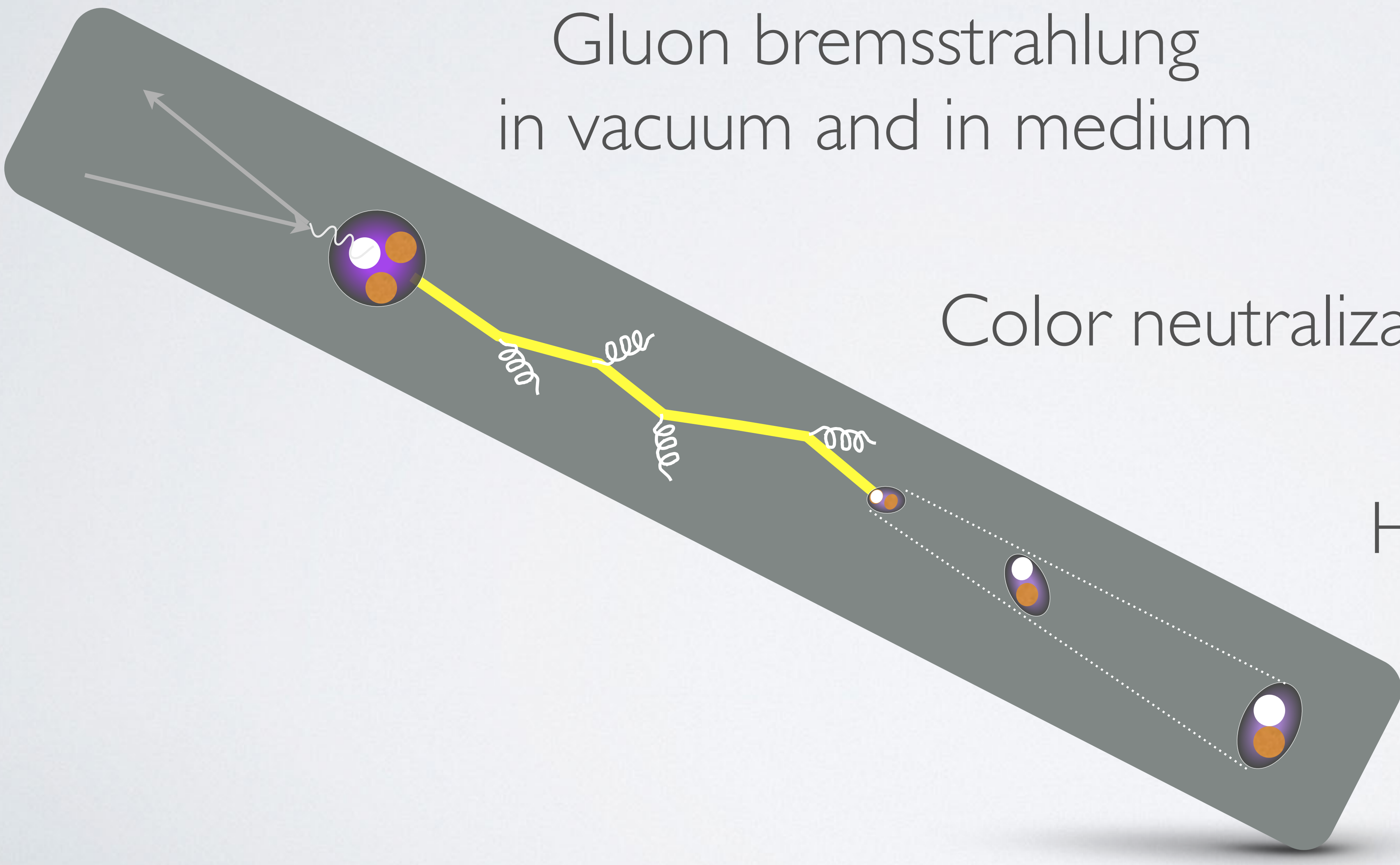


Partonic elastic scattering
in medium

Gluon bremsstrahlung
in vacuum and in medium

Color neutralization

Hadron formation



Brief Introduction

Physical picture for semi-inclusive DIS on nuclei for x>0.1:

- Struck valence quark absorbs full E and $\vec{p}$ of virtual photon, separates from nucleon remnant

- Colored quarks propagate, emitting ‘vacuum’ gluons and medium-stimulated gluons. ‘String breaking, $q\bar{q}$ pair production.’ ‘Parton showers.’ *Medium*: broadening of p_T, partonic energy loss.

- Color singlet pre-hadrons form at various times. *Medium*: elastic and inelastic interactions of (pre-)hadron.

Let’s test this picture and measure its parameters!

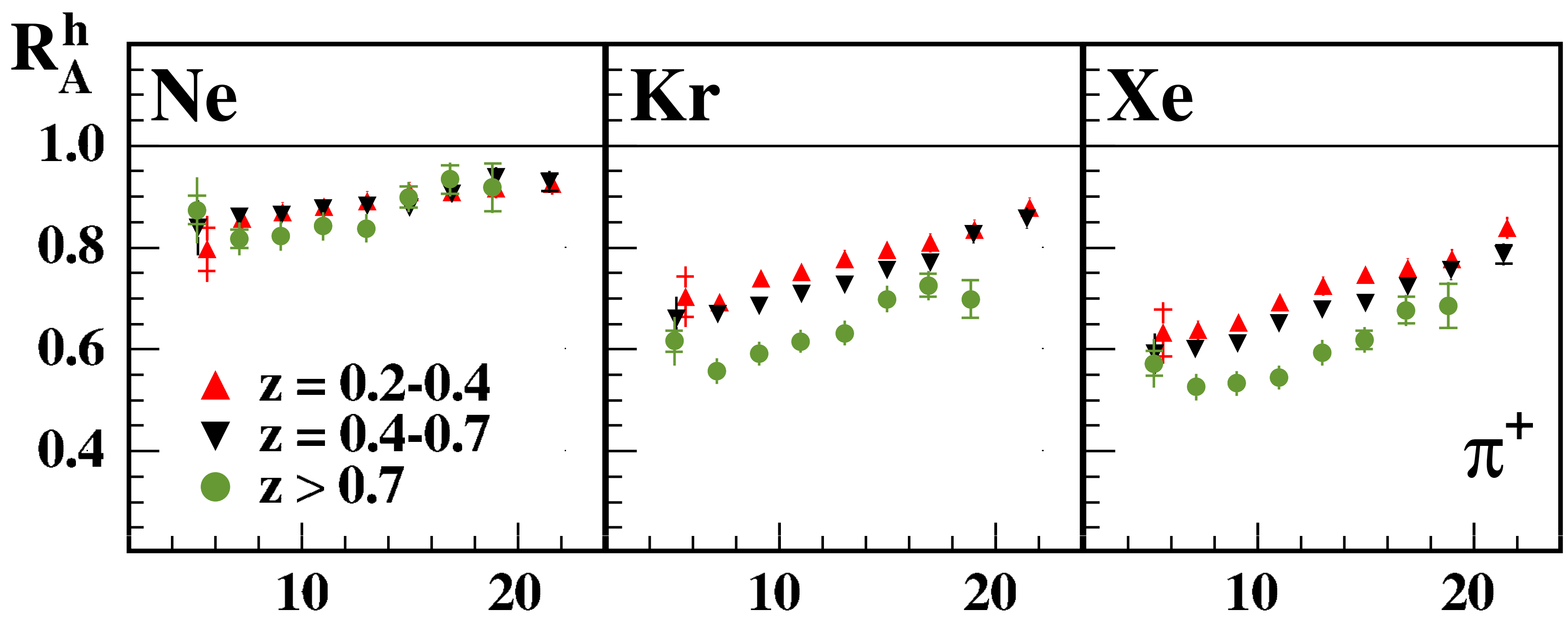
Production length extraction: results of feasibility study

Jorge López, Rodrigo Mendez,
Hayk Hakobyan, WB

Initial model concept:
B. Kopeliovich, A. Accardi

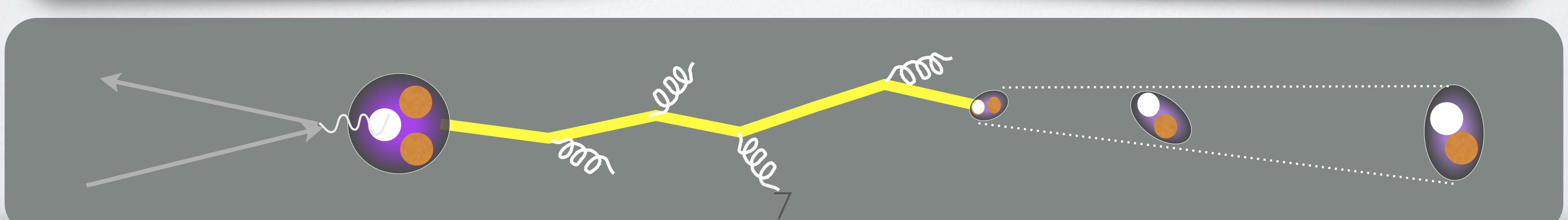
Tools

- Hadronic multiplicity ratio $R_h = \dfrac{\frac{1}{N_e^A(Q^2,\nu)} N_h^A(Q^2,\nu,z,p_T)}{\frac{1}{N_e^D(Q^2,\nu)} N_h^D(Q^2,\nu,z,p_T)}$
- From **ν** and **z** we learn about *time dependence* of hadronization mechanisms. ***However, detailed mechanism is debated.***



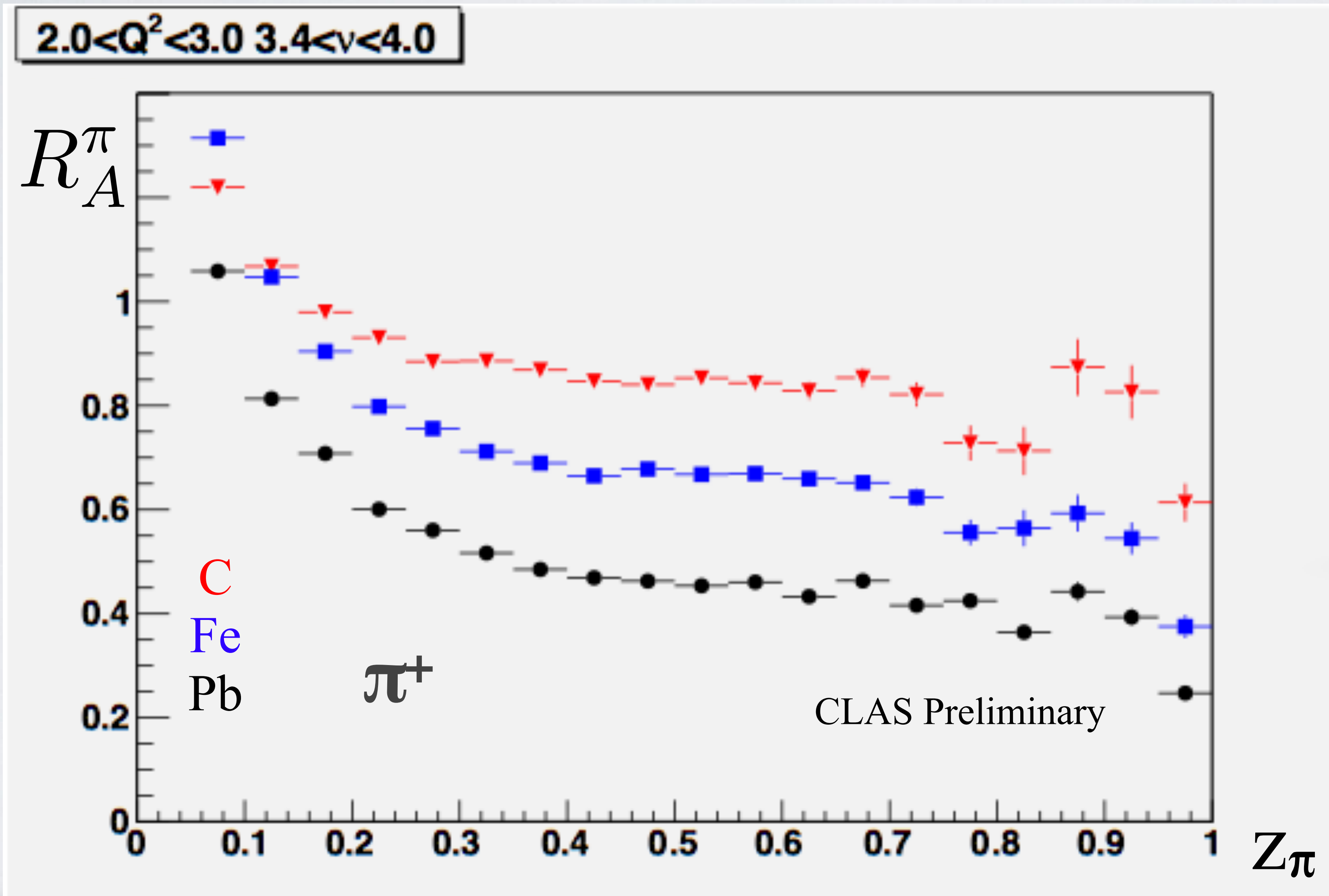
HERMES Coll., Eur. Phys. J. A (2011) 47: 113

$$z_\pi \equiv \frac{E_\pi}{\nu}$$

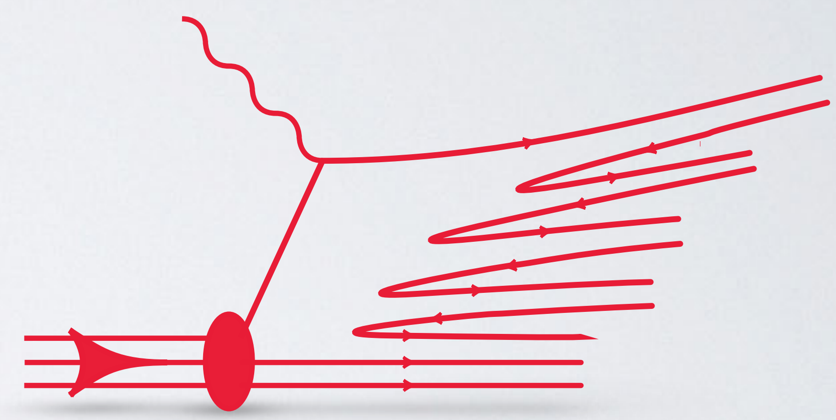


Virtual light quark lifetime from the Lund String model:

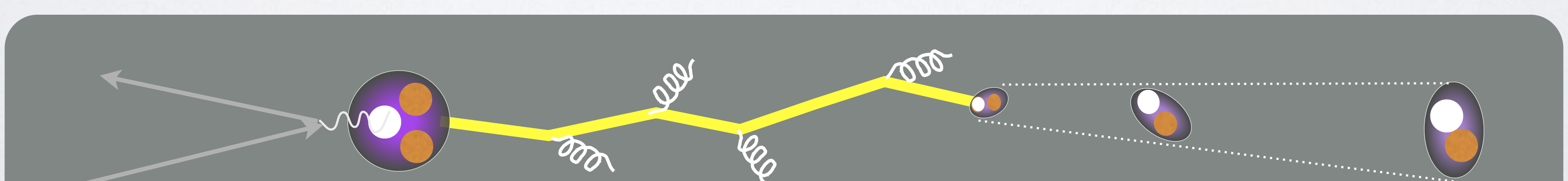
$$l_p = z\frac{(ln(\frac{1}{z^2}) - 1 + z^2)}{1 - z^2}$$



→ 0 for z=0 and z=1

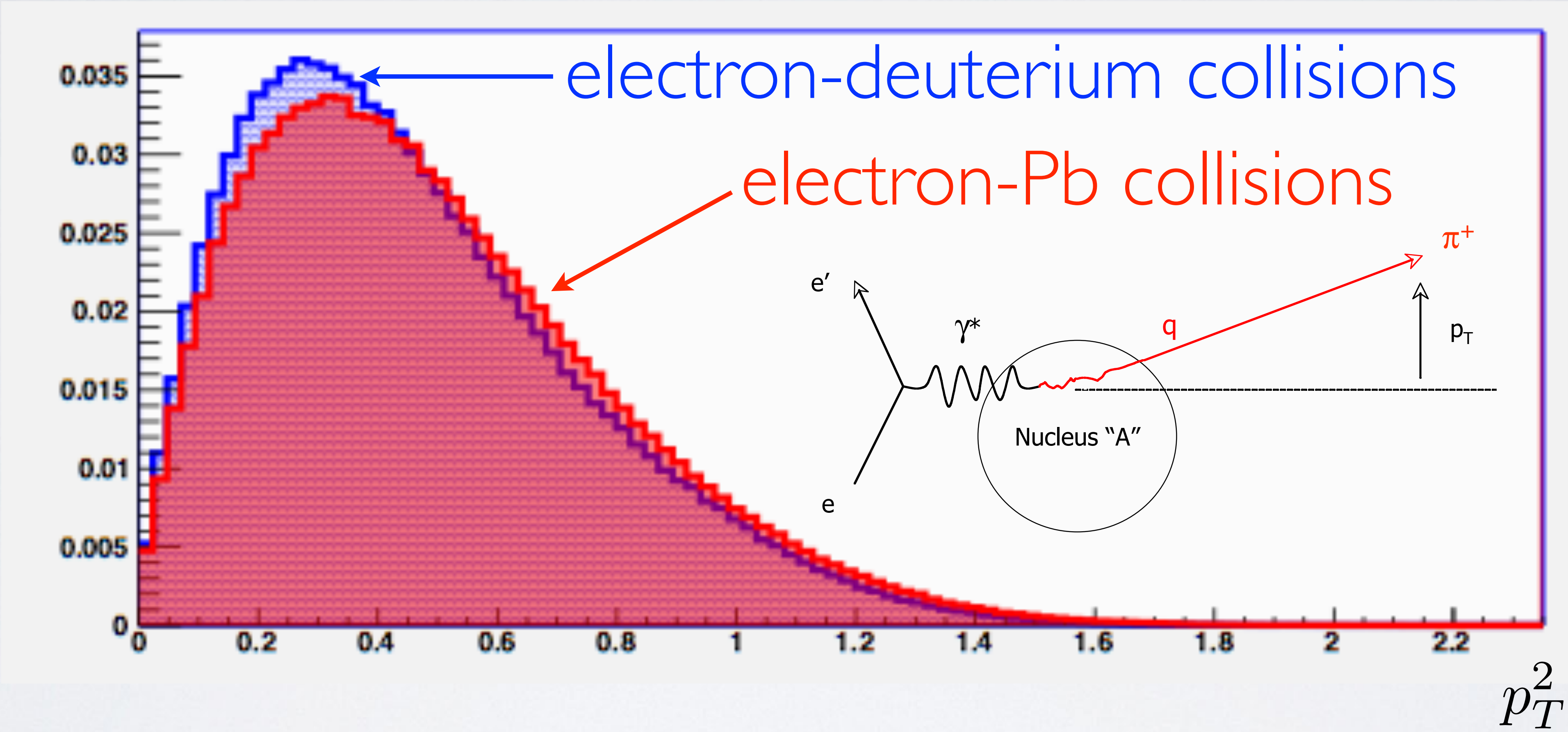


$$z_\pi \equiv \frac{E_\pi}{\nu}$$



Observable: p_T broadening

$$\Delta p_T^2 \equiv \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_D$$



p_T broadening is a tool: sample the gluon field using a colored probe:

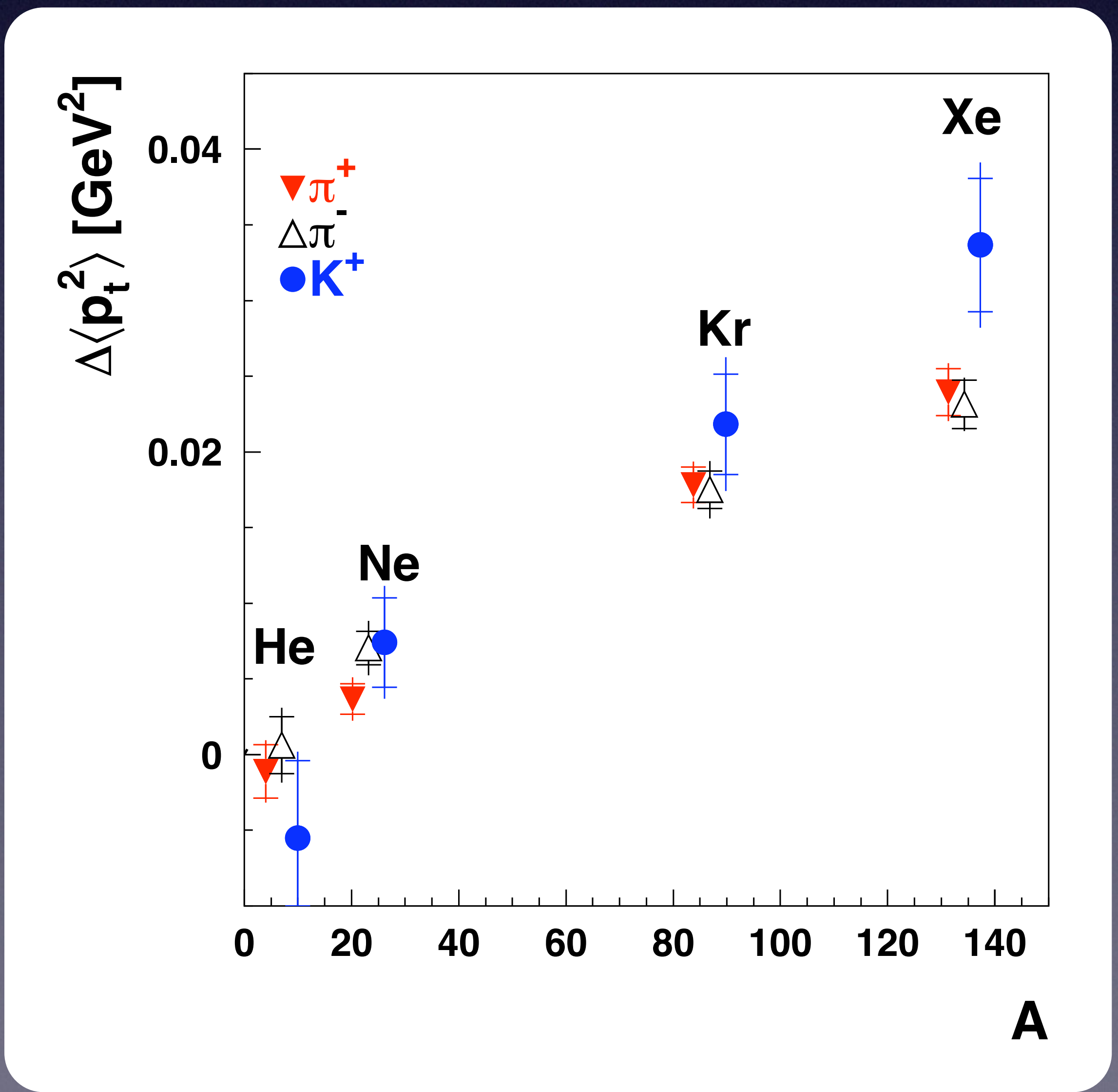
$$\Delta p_T^2 \propto G(x, Q^2)\rho L$$

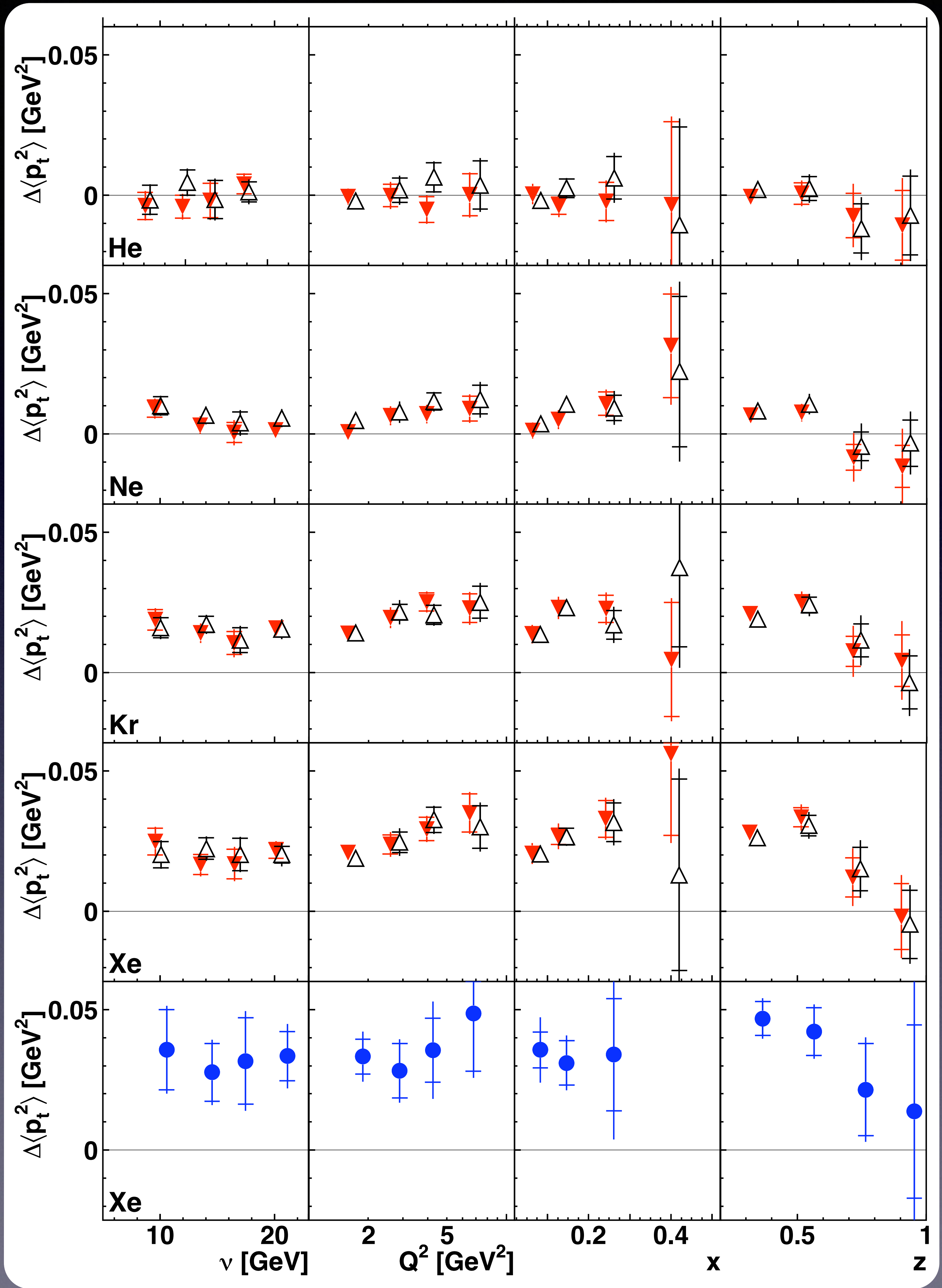
and radiative energy loss:

$$-\frac{dE}{dx} = \frac{\alpha_s N_c}{4} \Delta p_T^2$$

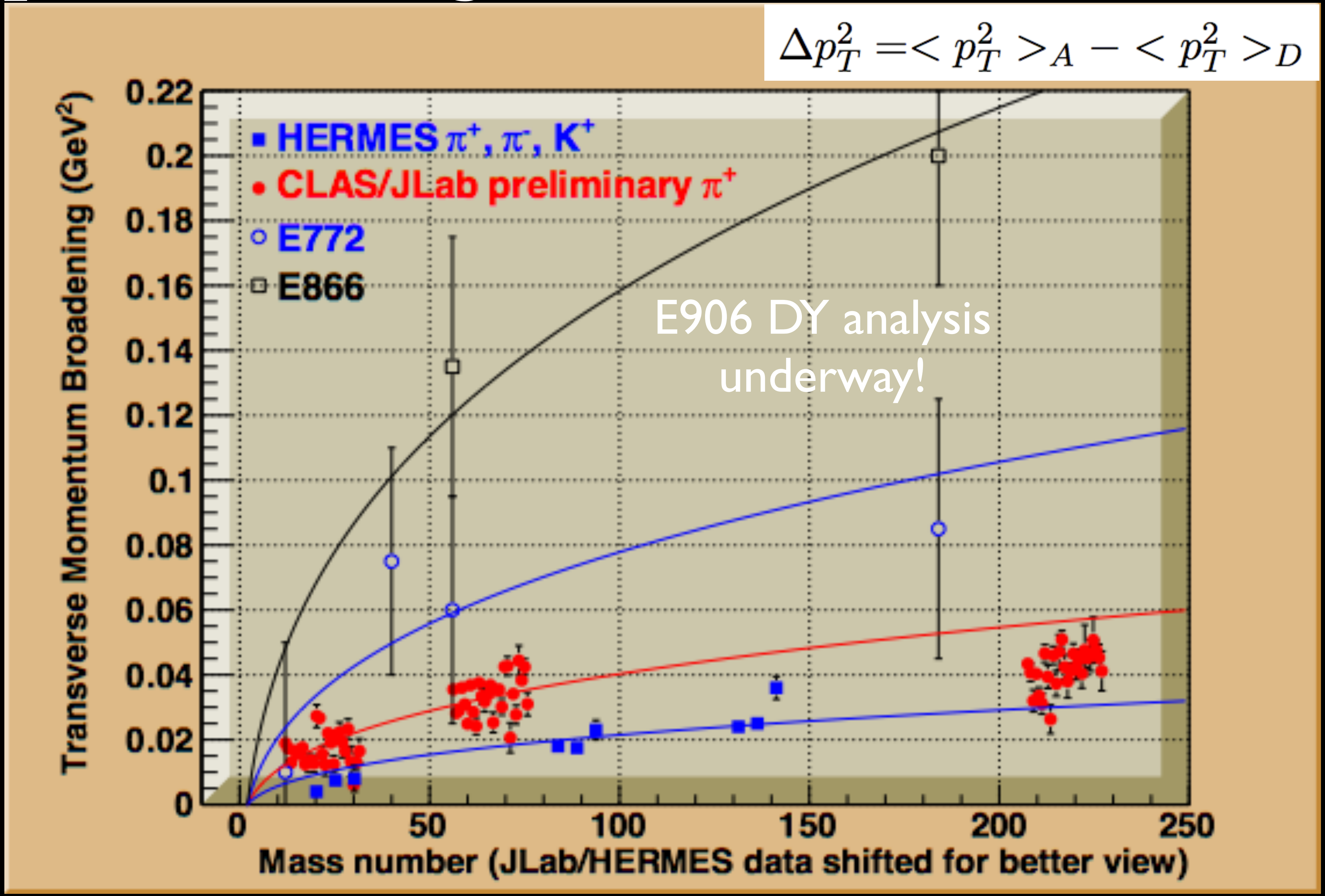
Hermes p_T broadening data

World's first comparison between pion and K^+ p_T broadening



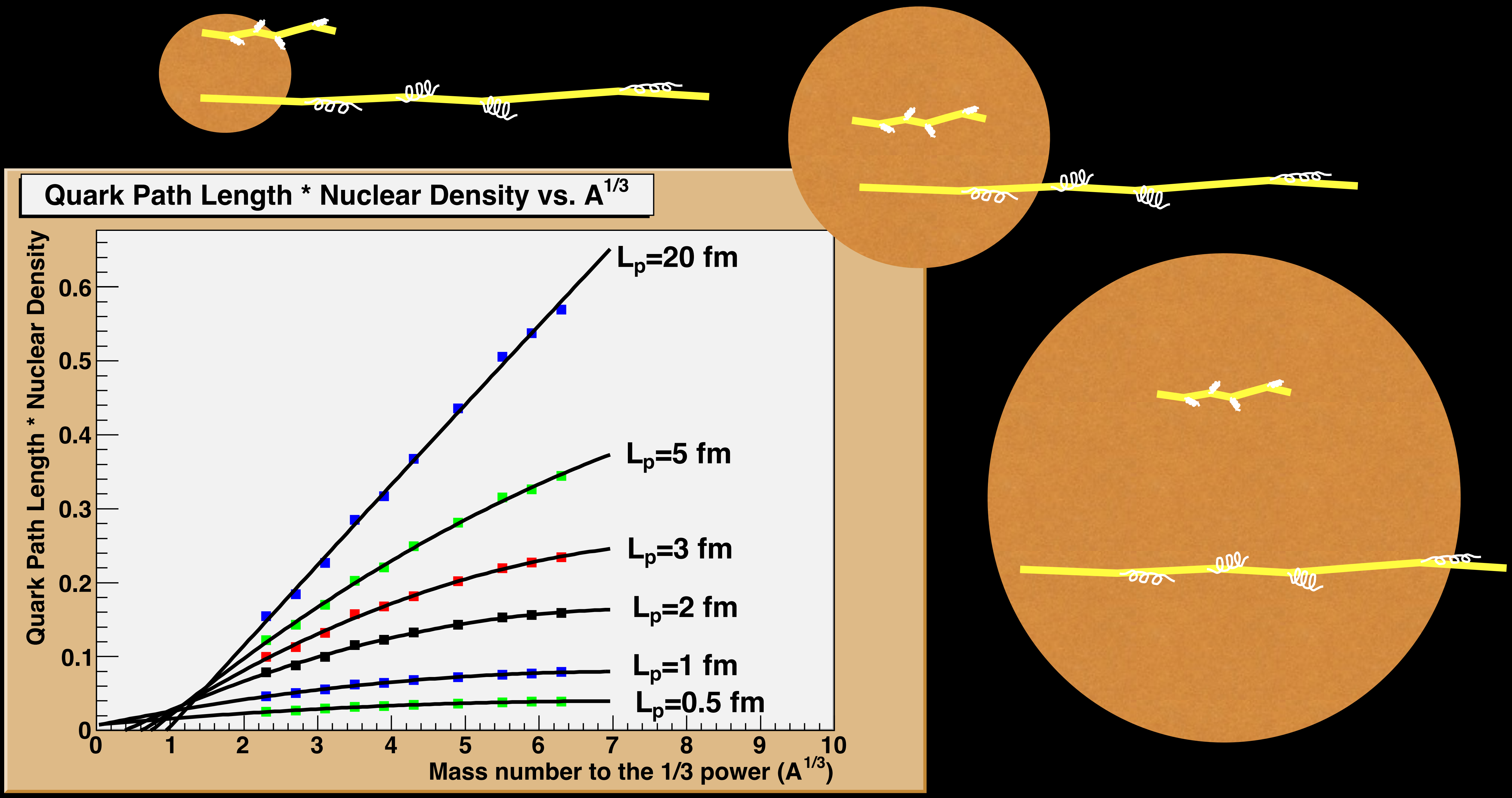


p_T broadening data - Drell-Yan and DIS



- New, precise data with identified hadrons!
- CLAS π^+: 81 four-dimensional bins in Q^2, ν, z_h, and A

Production Time Extraction - Geometrical Effects

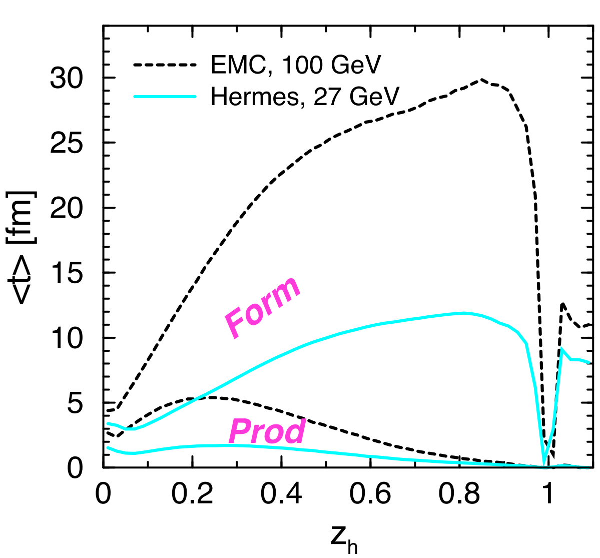


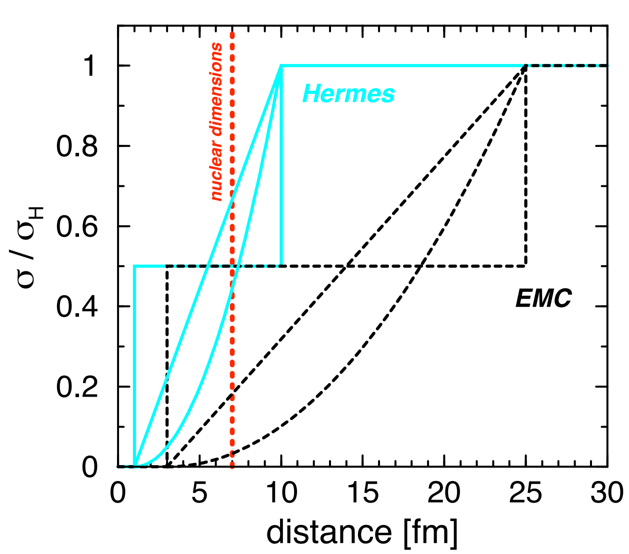
K. Gallmeister, U. Mosel
Nucl. Phys. A801:68-79, 2008
http://arxiv.org/abs/nucl-th/0701064v4

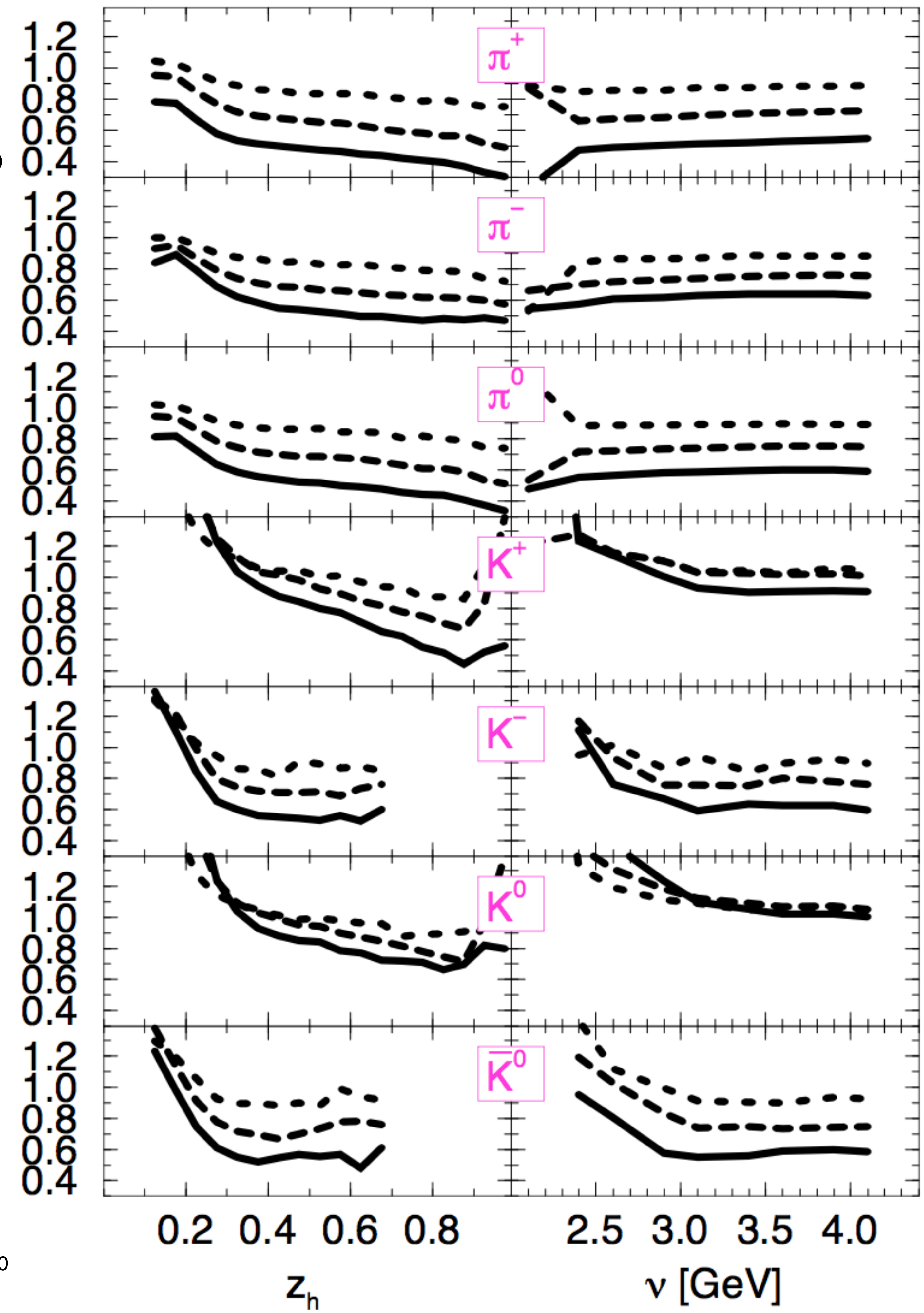
2008 prediction for CLAS6.
Cross section depends linearly on time:

$$\sigma^*(t)/\sigma = X_0 + (1 - X_0) \cdot \left(\frac{t - t_P}{t_F - t_P}\right)$$

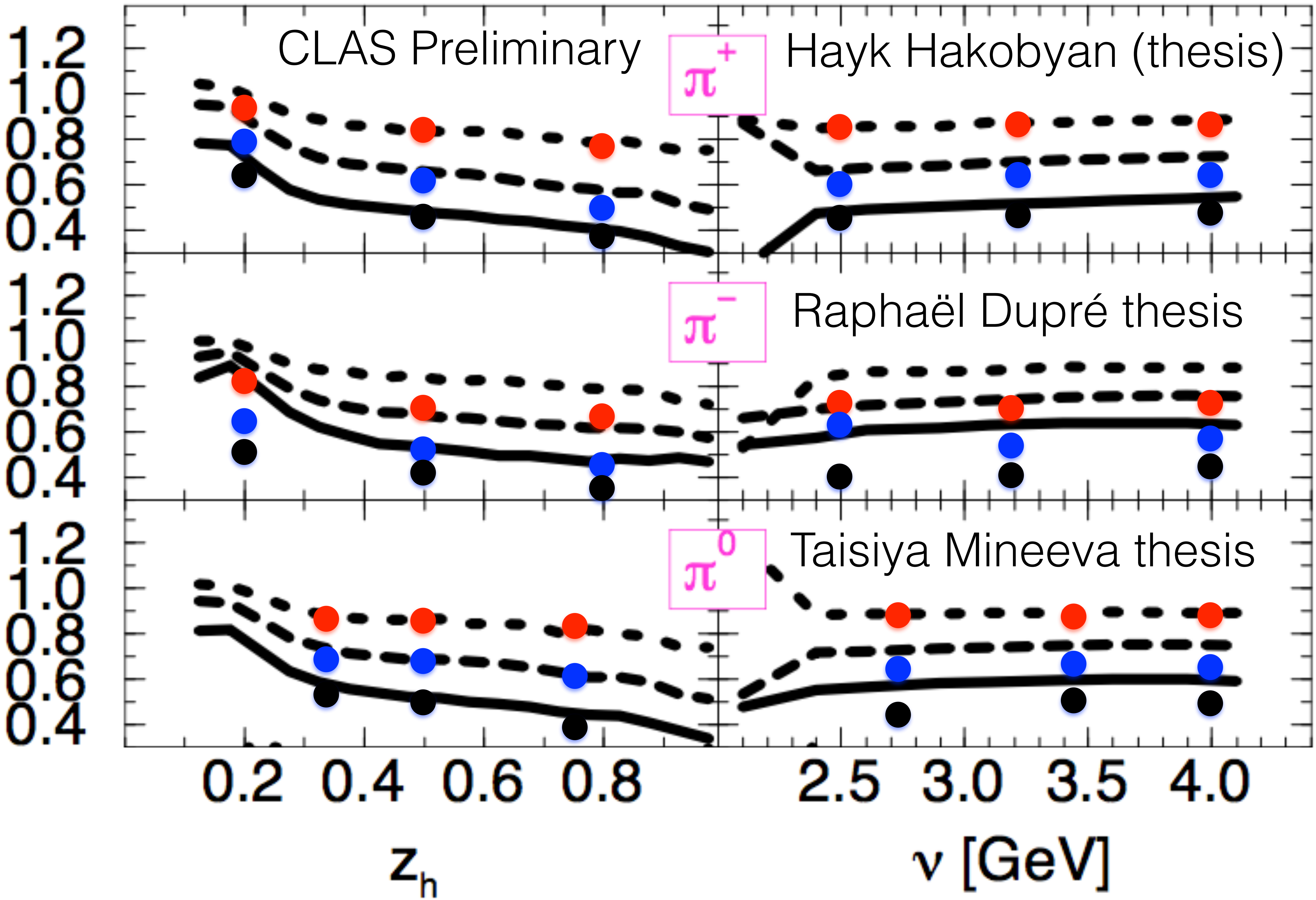
Production time = 0.5 fm/c

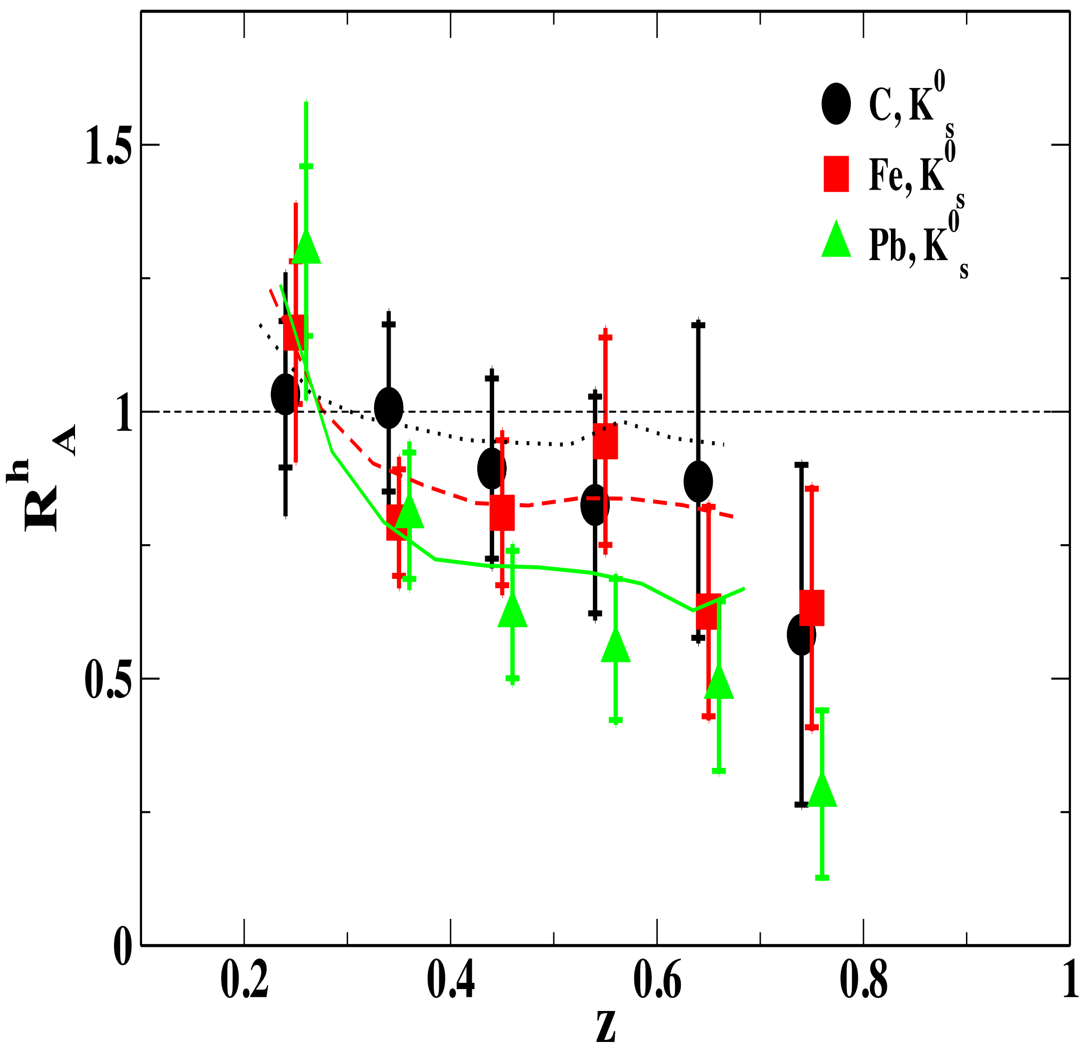




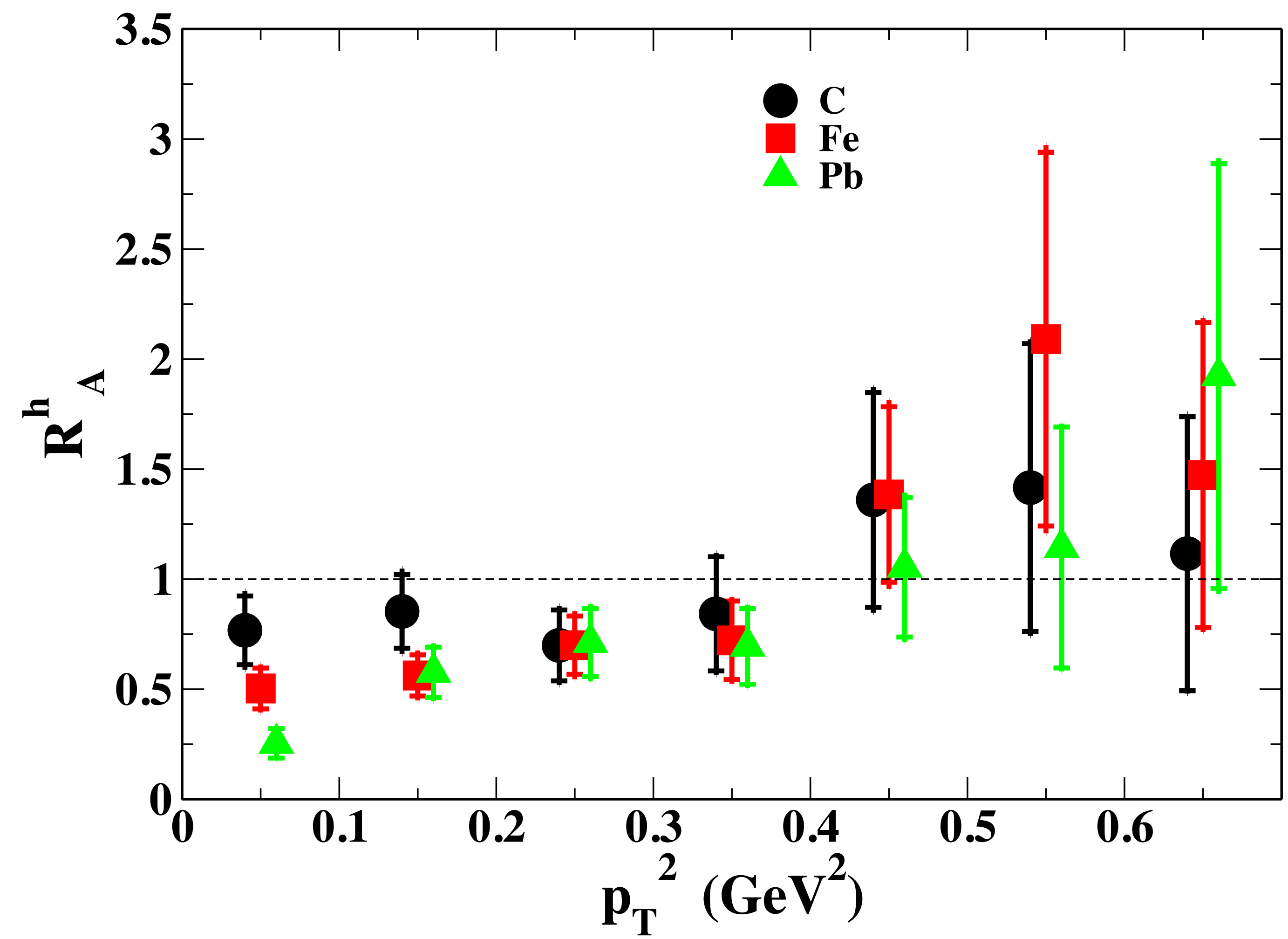


Comparisons to preliminary CLAS data (PhD theses, 1-D only)





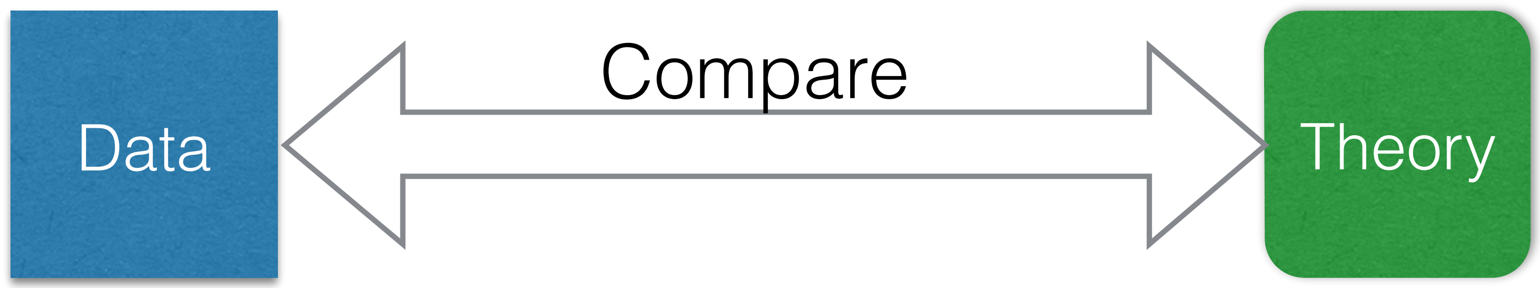
CLAS K0 multiplicity ratio and Mosel model



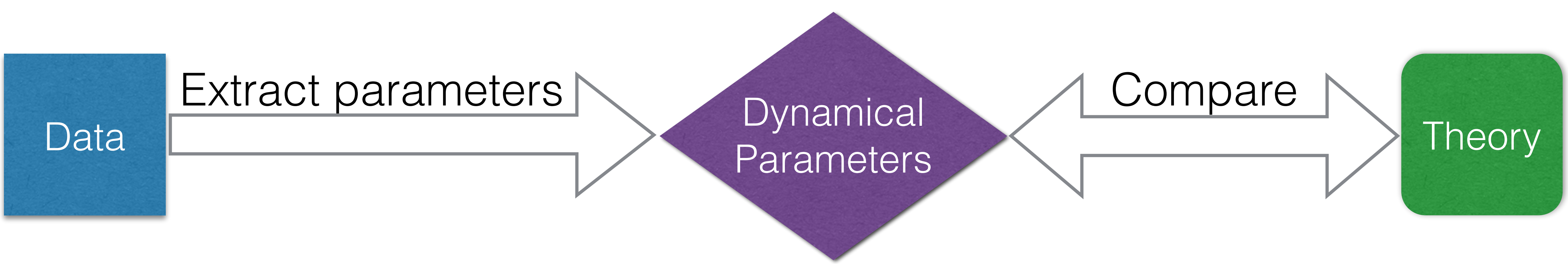
A. Daniel, K. Hicks et al. PLB 706 (2011) 26-31.

Geometric model to extract dynamical parameters

Often data are directly confronted with theory calculations:



Sometimes there is an intermediate step, when a reliable procedure extracts essential information from data:



In the following we explore such a procedure

Model description I

- Propagating quark causes p_T broadening of hadron
- Propagating quark loses energy by gluon emission, resulting in a reduction of hadron z values - z-shift
- Propagating (pre-)hadron “disappears” when it undergoes an inelastic interaction with cross section σ
- Implemented as a Monte Carlo calculation
- Realistic nuclear density

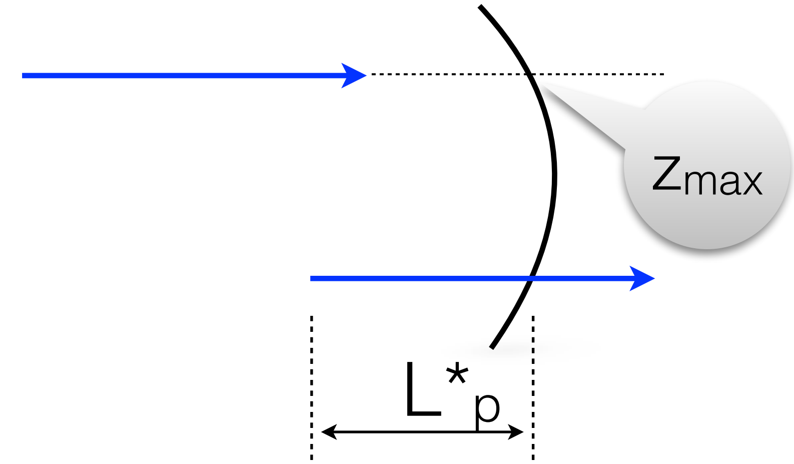
Model description II

Model implemented with 3, 4 or 5 **parameters**:

1. **q-hat** parameter (transport coefficient) that sets the scale of p_T broadening
2. Production length $\mathbf{L_p}$: distance over which p_T broadening and energy loss occur. Assumed exponential form
3. **Cross section** for <u>pre</u>hadron to interact with nucleus.

4. **Shift in z** caused by quark energy loss in medium
5. Average **distance between scatterings** or “mean free path” l_0 (alternative form of pT broadening, proportional to $L_p * \log^2(L_p/l_0)$)

Model description III



$$\langle \Delta p_T^2 \rangle = \langle\ \hat{q}_0 \cdot L_p^* \int_{z=z_0}^{z=z_0+L_p^*} \rho(x_0, y_0, z)\ dz\ \rangle_{x_0, y_0, z_0, L_p}$$

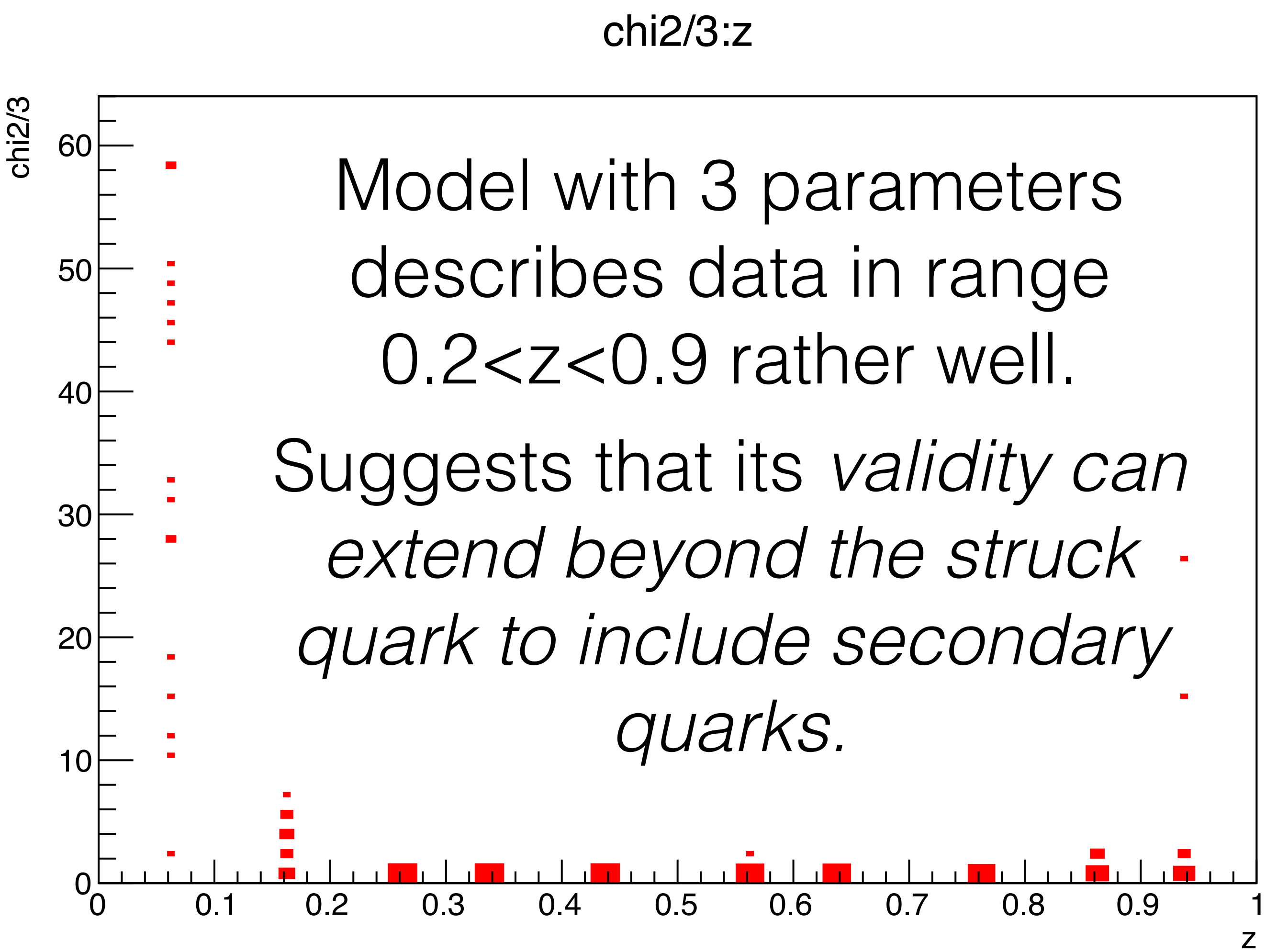
L_p is distributed as exponential
x_0, y_0, z_0 thrown uniformly in sphere, weighted by $\rho(x,y,z)$
$L^*_p = L_p$ except where truncated by integration sphere

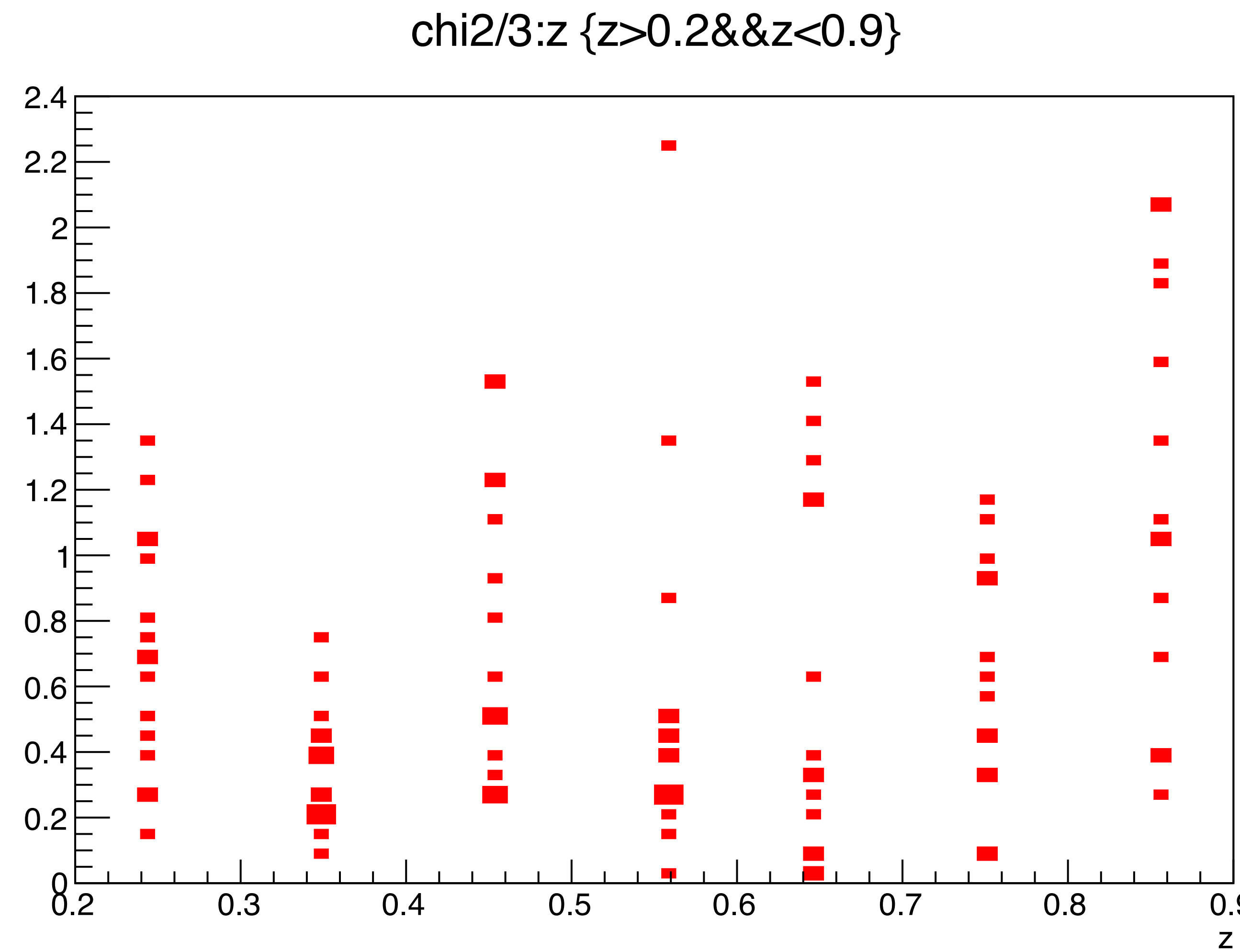
$$\langle R_M \rangle = \langle\ exp(-\sigma \int_{z=z_0+L_p}^{z=z_{max}} \rho(x_0, y_0, z)\ dz\ )\ \rangle_{x_0, y_0, z_0, L_p}$$

The above are computed sequentially (same x_0, y_0, z_0, L_p)

Data in (x, Q^2, z) bin: fitted to model, $3^{(+)}$ parameters: $\hat{q}_0$, $<L_p>$, σ
No kinematics/dynamics are assumed; they emerge from fit

Approximate systematic errors: 3% for multiplicity ratio, 4% for p_T broadening

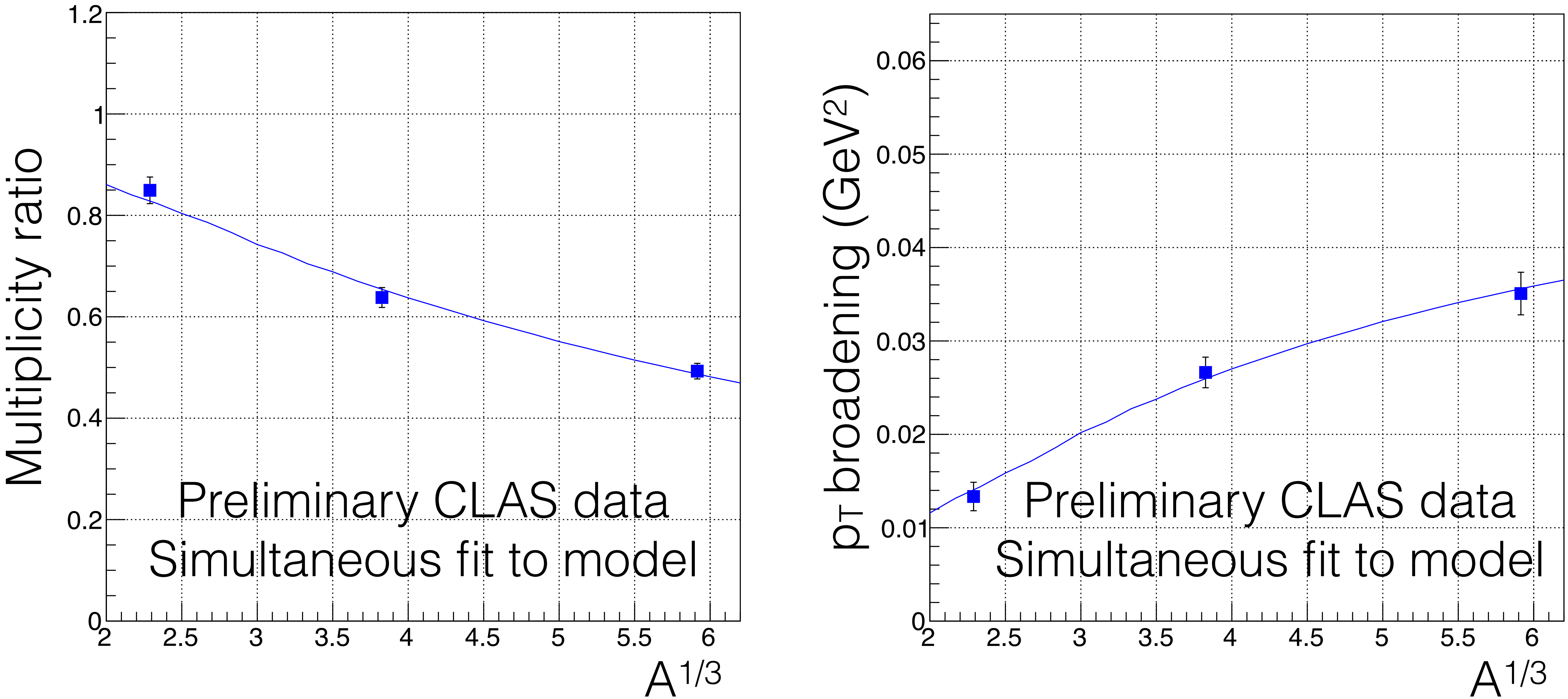




chi2 comparisons:

Average <chi2/dof>	3 parameters	4 parameters	5 parameters
chi2/dof	**3.9**+/-8.9, 153 bins	**2.1**+/-3.8, 153 bins	**3.5**+/-4.8, 153 bins
chi2/dof+quality cuts (QC)	**1.2**+/-1.3, 90 bins	**1.7**+/-1.7, 103 bins	**1.7**+/-1.7, 115 bins
chi2/dof, 0.2<z<0.9	**0.67**+/-0.5, 107 bins	**0.96**+/-0.75, 107 bins	**1.9**+/-1.5, 107 bins
chi2/dof, QC, 0.2<z<0.9	**0.75**+/-0.5, 68 bins	**1.02**+/-0.78, 73 bins	**1.04**+/-0.77, 80 bins

Example of fit (one of 153 bins in x, Q^2, and z)



$\langle x \rangle=0.166$, $\langle Q^2 \rangle=1.17\ GeV^2$, ($\langle \nu \rangle=3.76$ GeV), $\langle z \rangle=0.445$

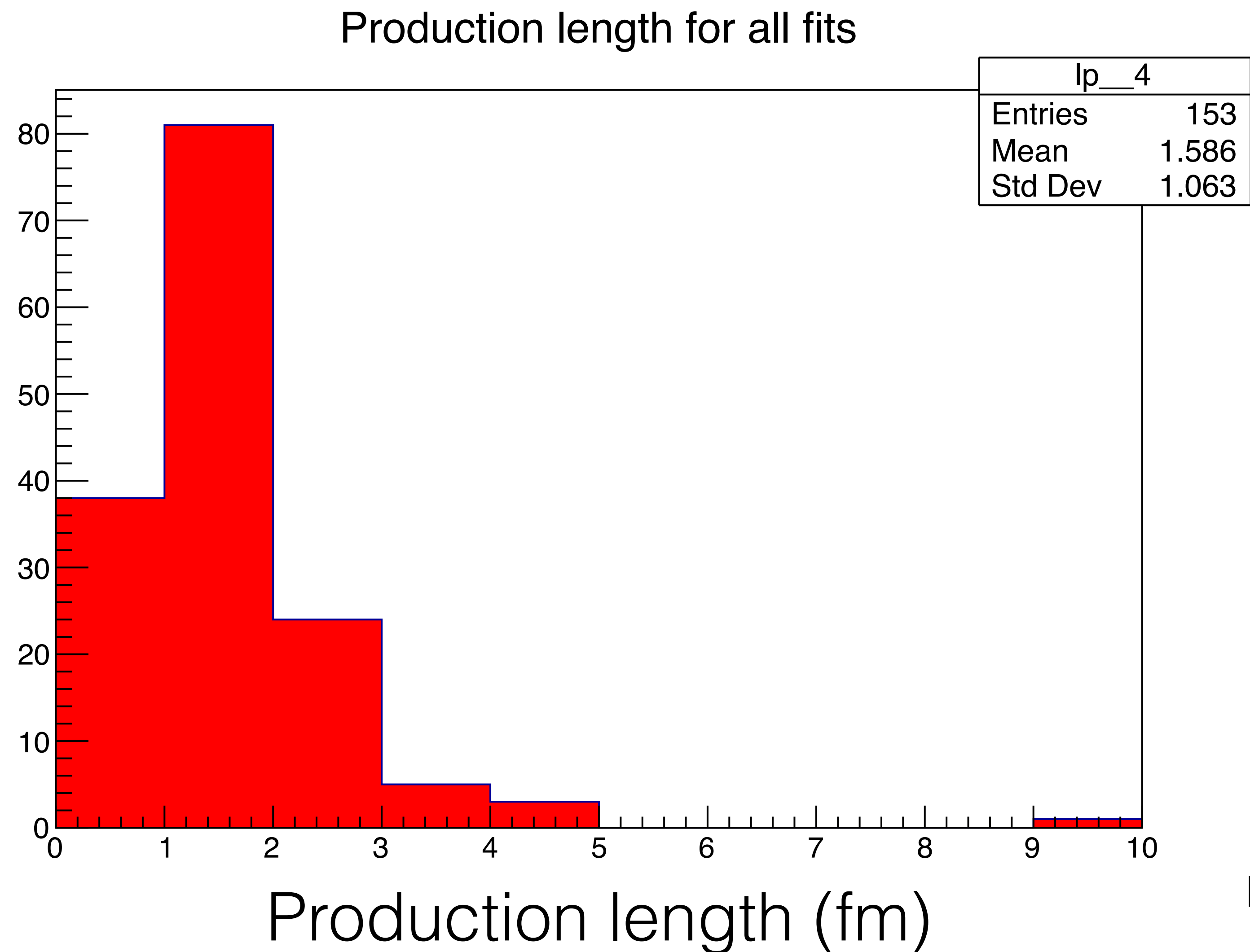
$L_p=1.8\pm0.4$ fm

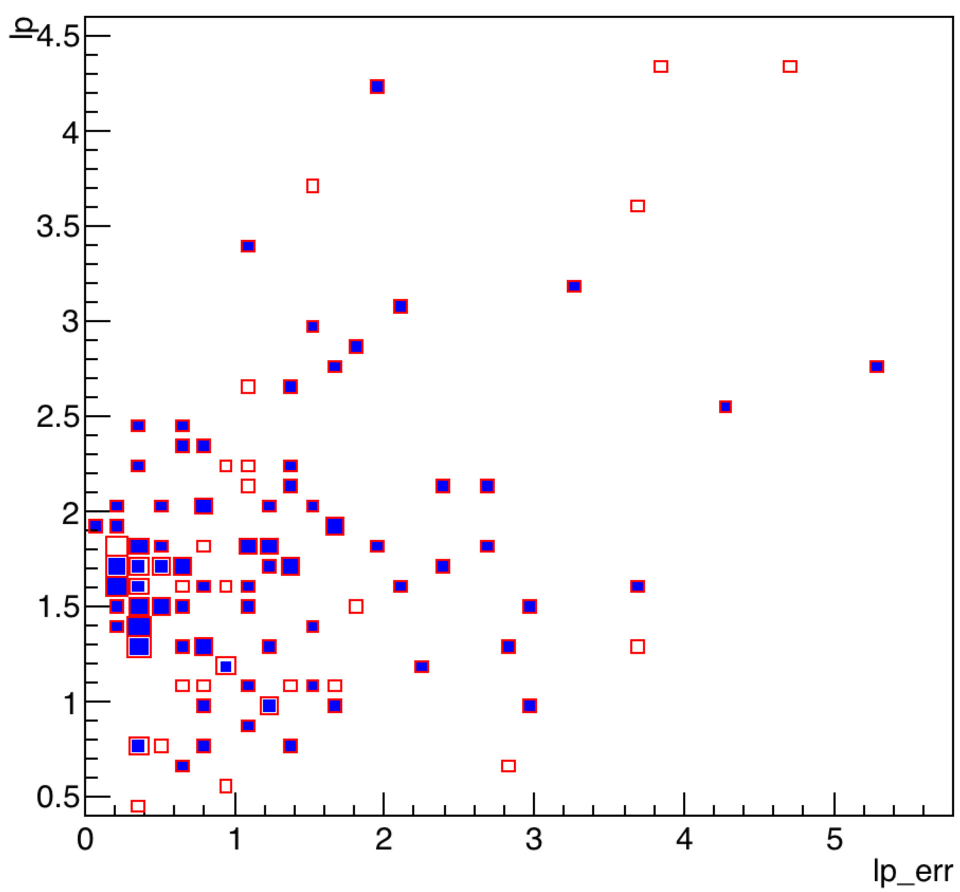
$\chi^2/dof = 0.5$

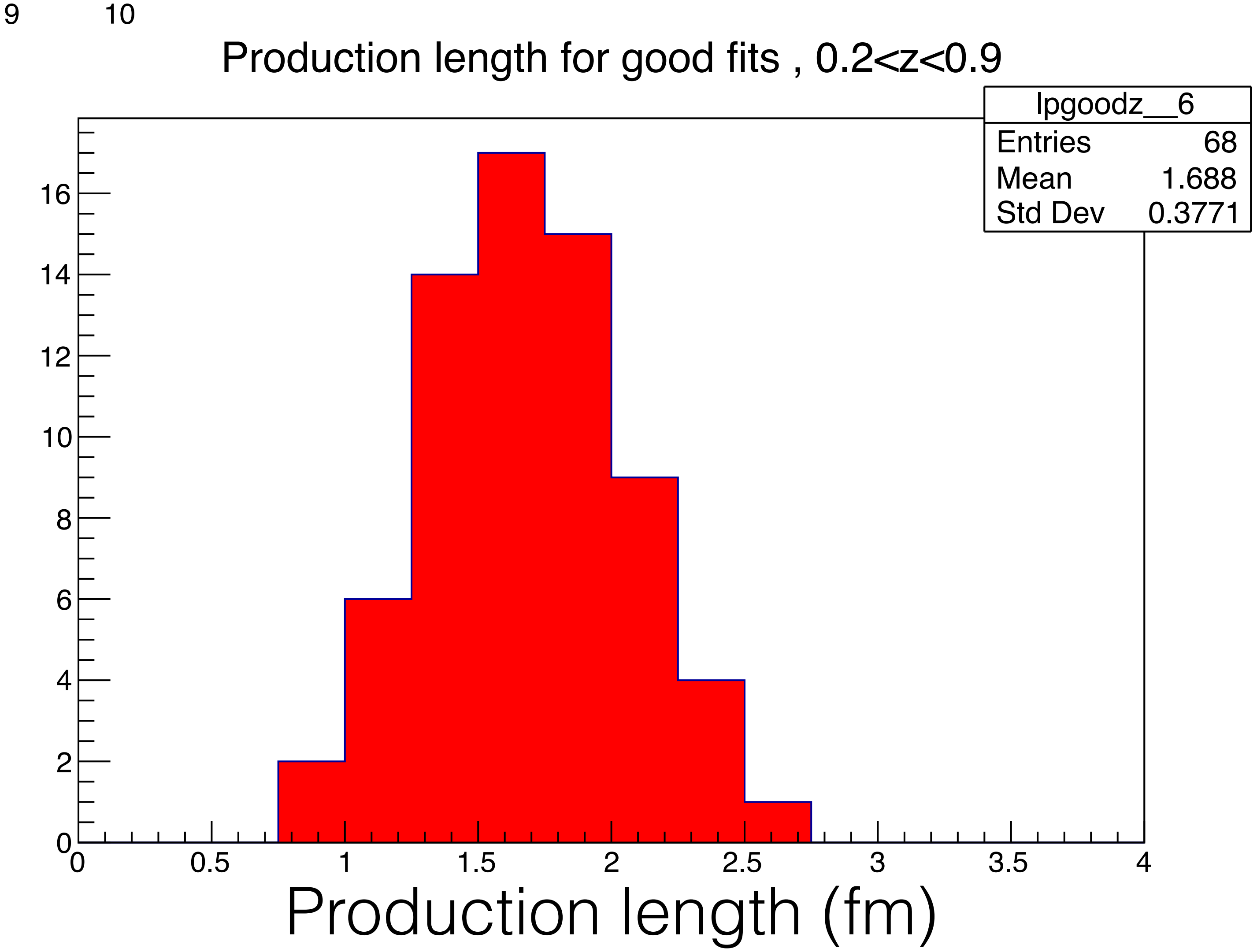
Simultaneous fit *couples* p_T broadening to multiplicity ratio

04 1.25 0.145 0.45 2.23297 1.79603 20.0934 0 0 0.737494 0.415131 3.17692 0 0 1.48512

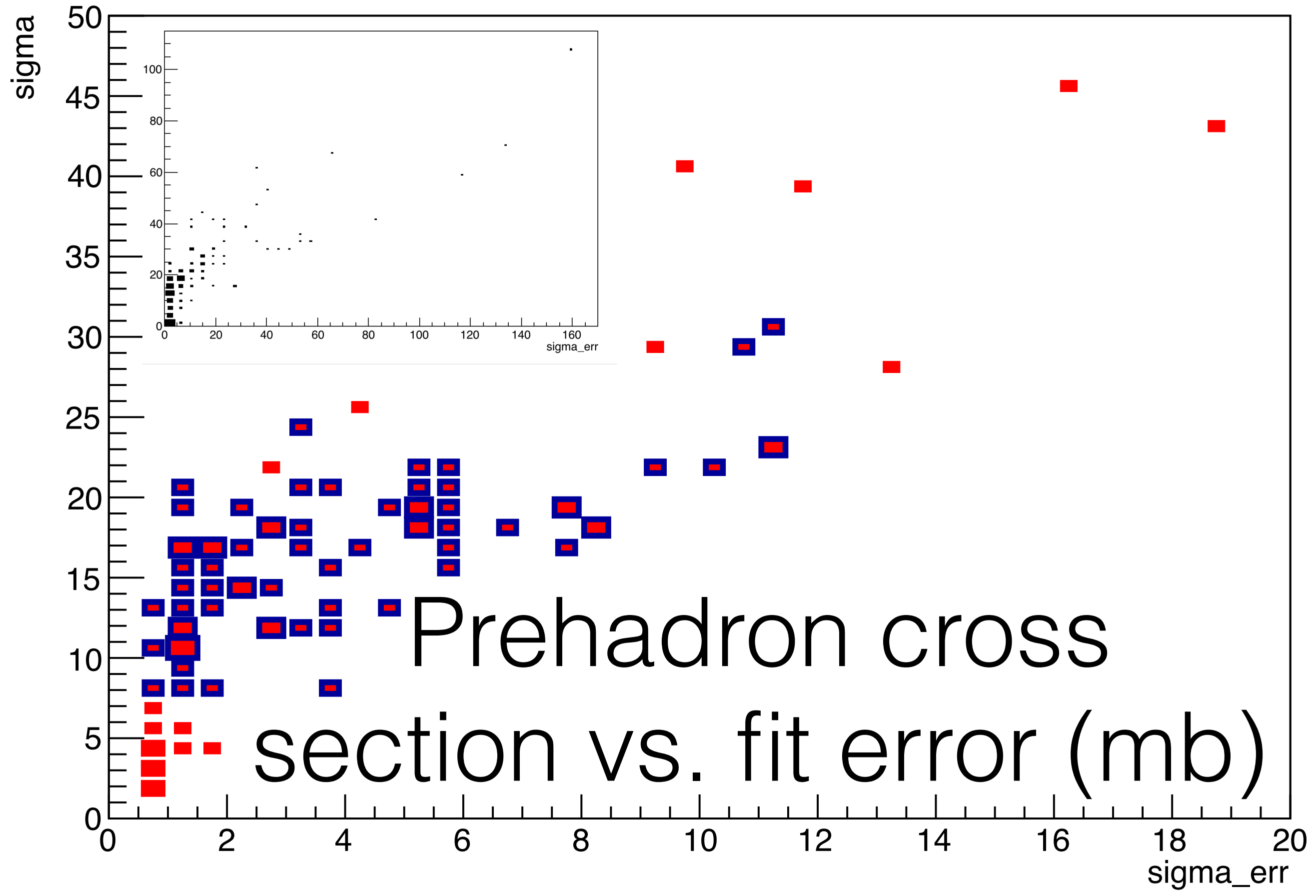
Three-parameter model results for production length







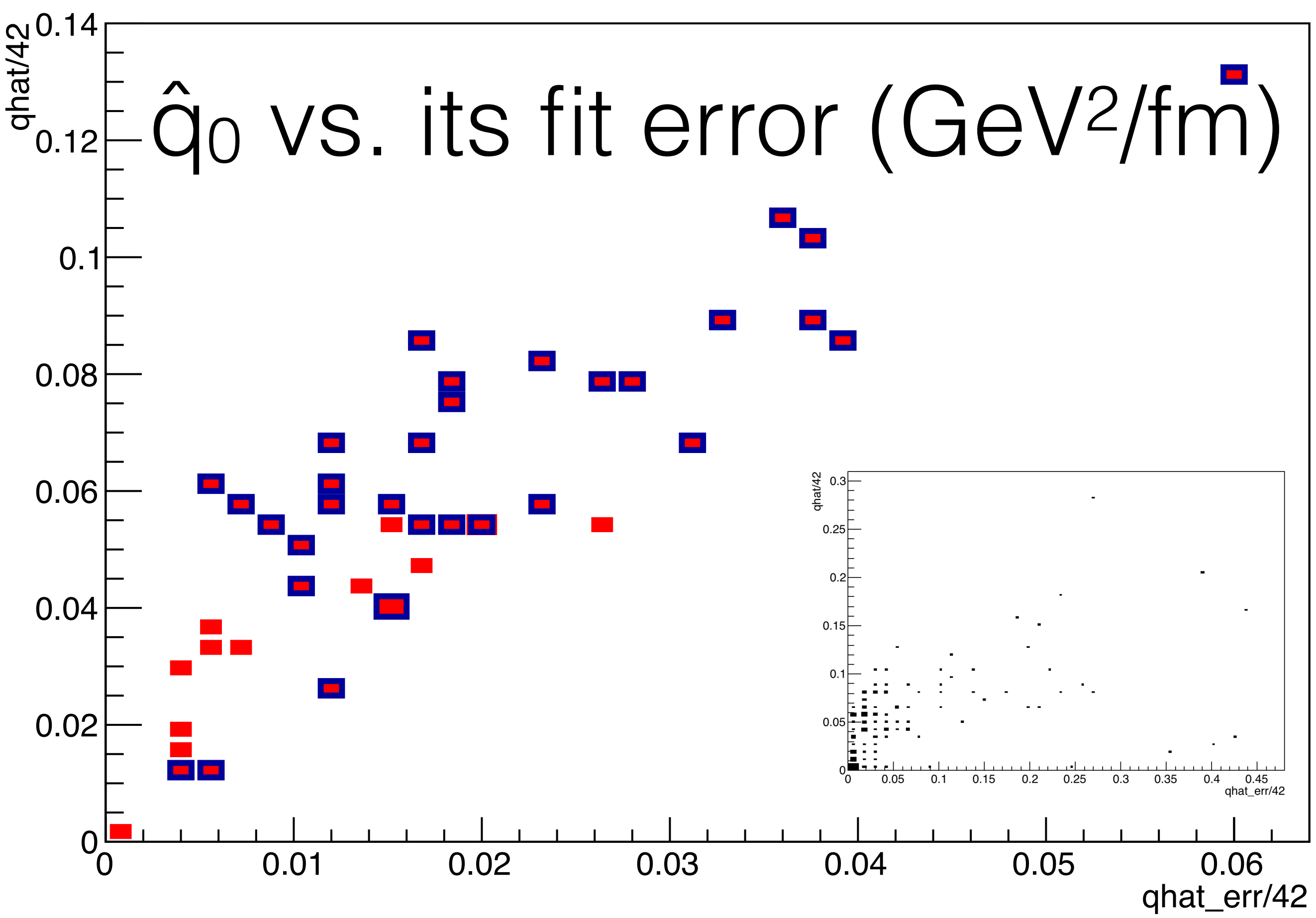
Other fit parameters from model



Red: prehadron cross section with <50% fit error

Blue: prehadron cross section with <50% fit error and 0.2<z<0.9

Inset: no cuts

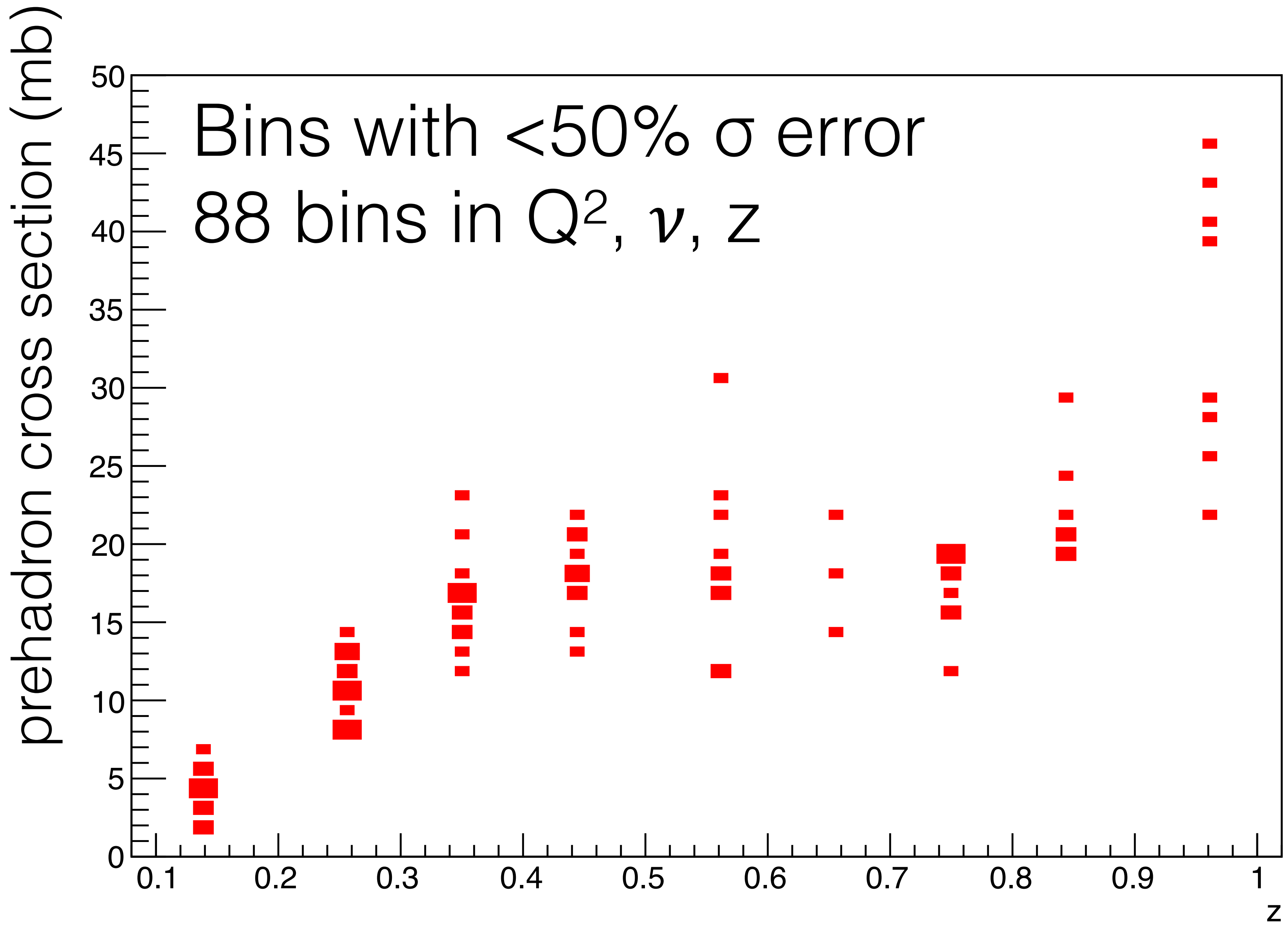


Red: $\hat{q}_0$ with <50% fit error

Blue: $\hat{q}_0$, <50% fit error and 0.2<z<0.9

Inset: $\hat{q}_0$ error < 1 GeV^2/fm

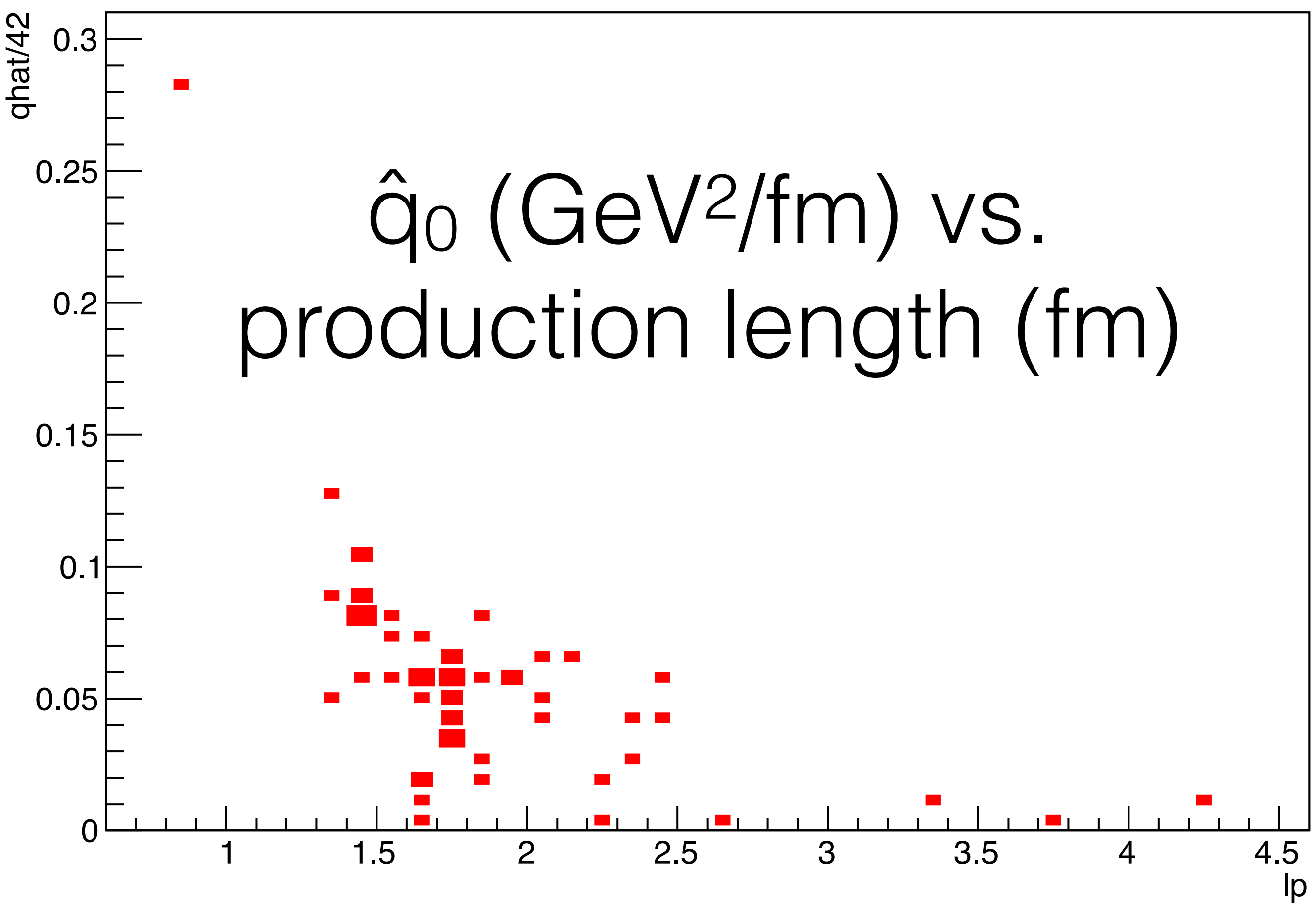
Prehadron cross section vs. z



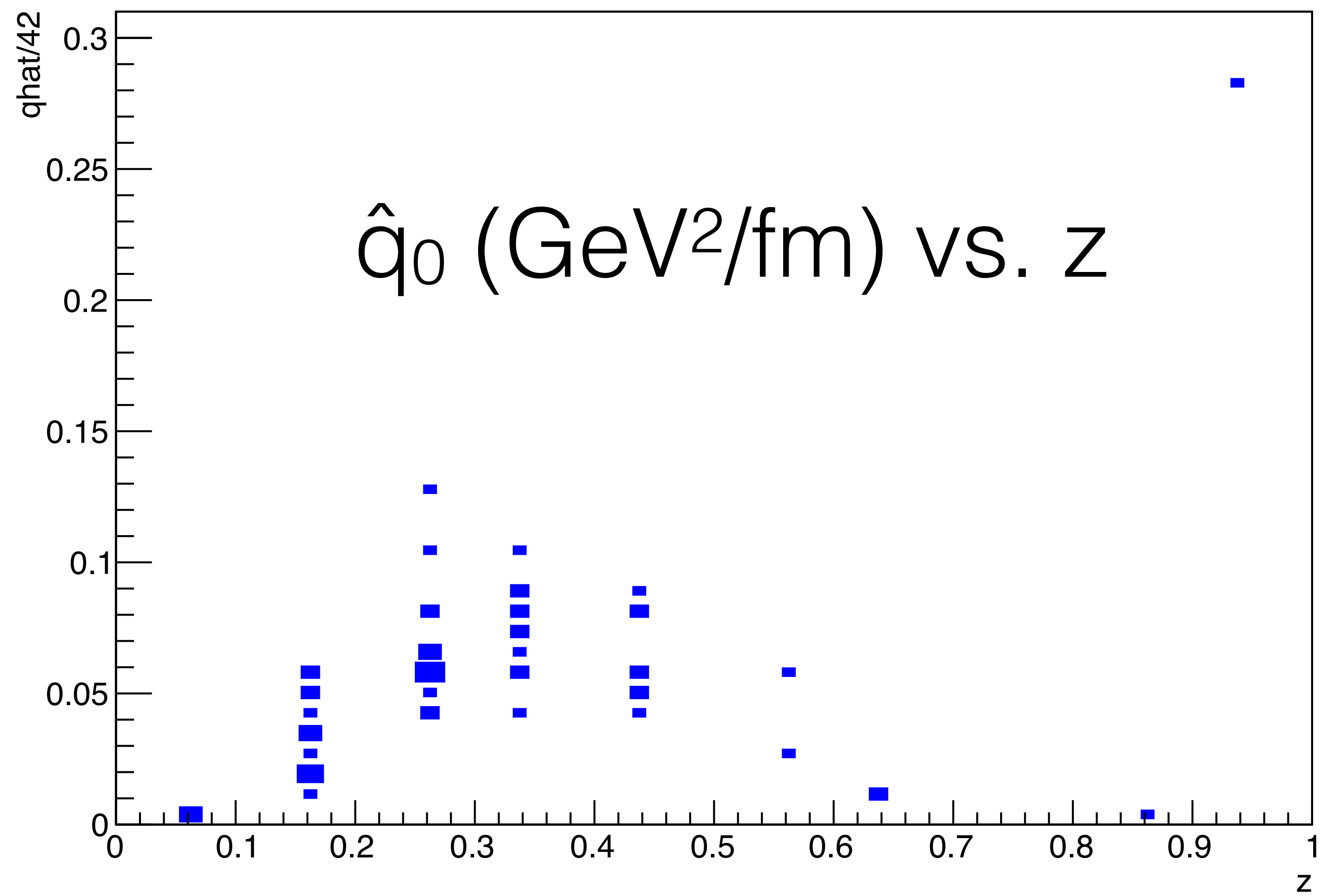
- Less than πN cross section except at high z - *good!*
- Reduction at low z is artificial: caused by bin migration of inelastic interaction products in the multiplicity ratio, which is >1.

$\hat{q}_0$ vs. L_p and z from model fit

57 bins in Q^2, v, z



Requirements for these plots: $\hat{q}_0<1$ and production length error < 50%



Z dependence is reminiscent of Lund String Model function for production length

Time dilation test

- Gluon emission is fundamentally a time-based process (nuclear effects decrease at high energies)
- A strong validation of this model would be the observation of **time dilation of $\tau_p \equiv L_p/c$**

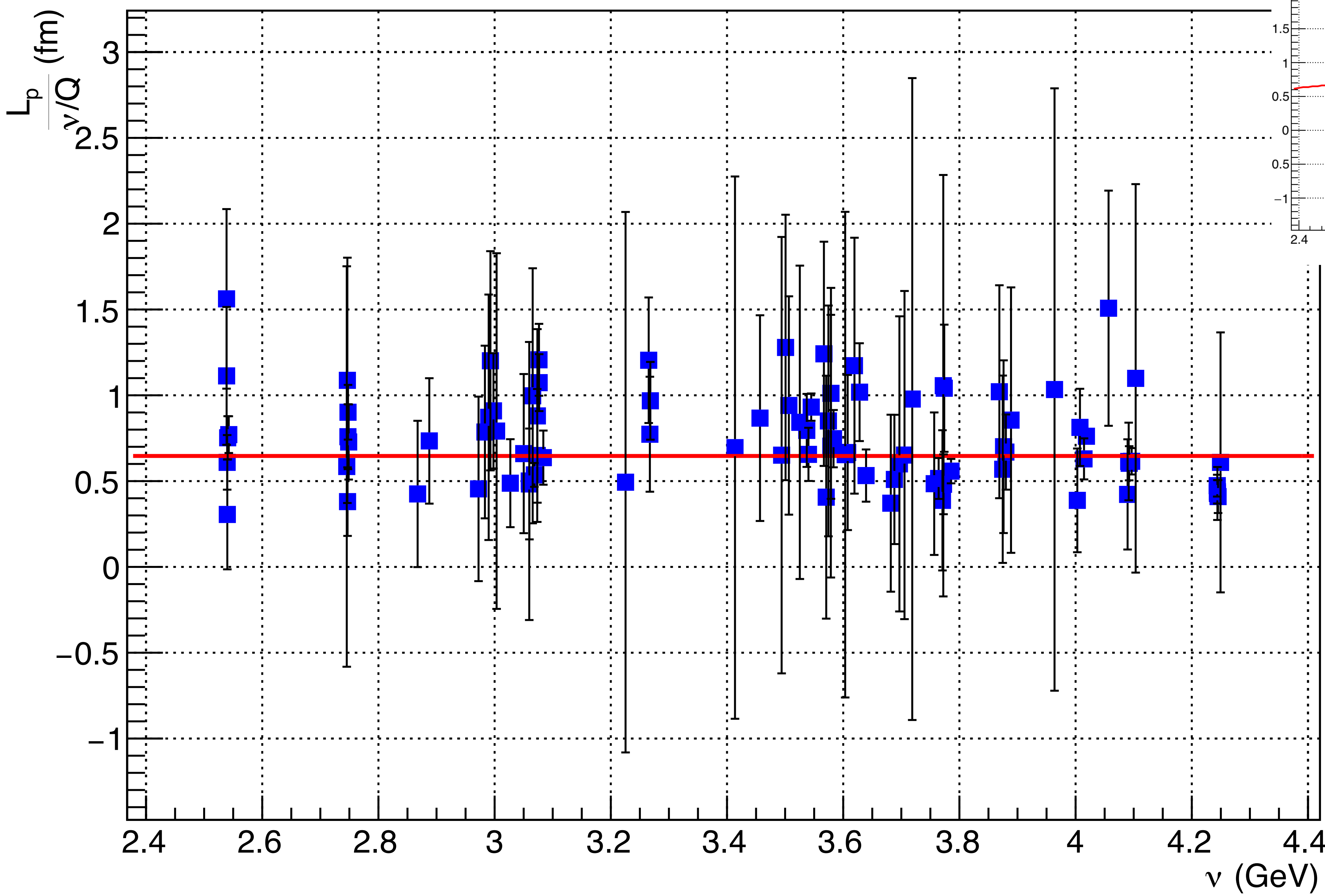
$$\tau_p = \gamma \cdot \tau_0 = (E/m) \cdot \tau_0 = (\nu/Q) \cdot \tau_0$$

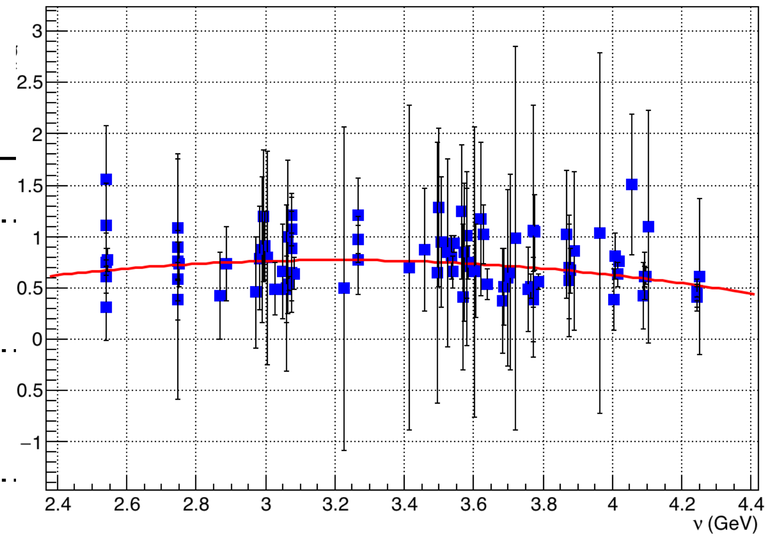
The above hypothesis comes from (1) single photon exchange approximation, (2) the quark absorbs all the energy and momentum of the virtual photon, and (3) the identification of $Q \equiv (Q^2)^{0.5}$ with quark mass (virtuality).

➨ fit $L_p/(\nu/Q)$ to a constant (τ_0): good fit? reasonable values?

γ varies from 1.9 to 3.5 for these data; almost a factor of 3

Production length extraction





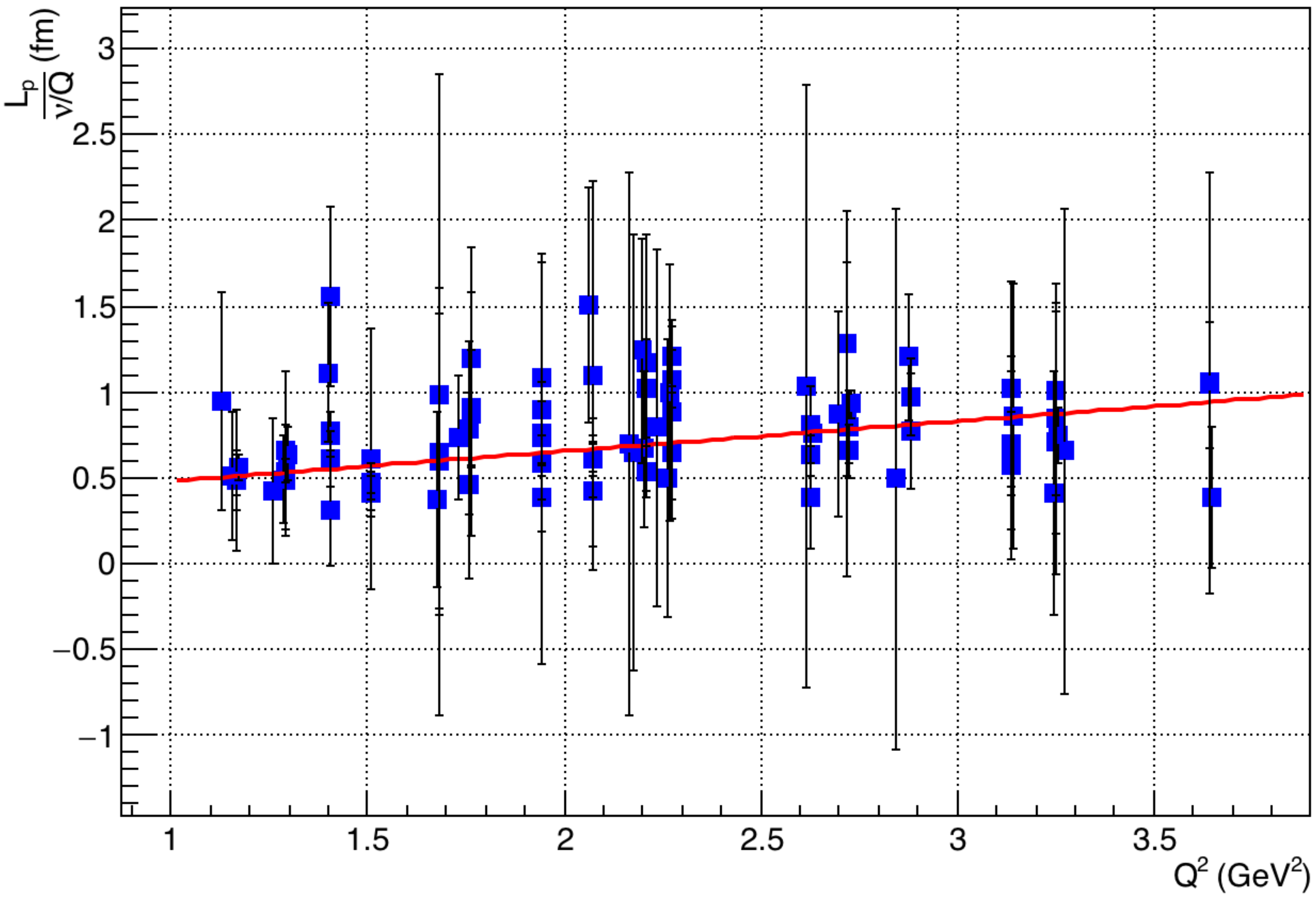
Extracted value of the lab-frame production length gives

<L_p>=0.65±0.02*(ν/Q) fm

Chisquared/dof=1.1, 3 parameter model, in 88 Q^2,x,z bins

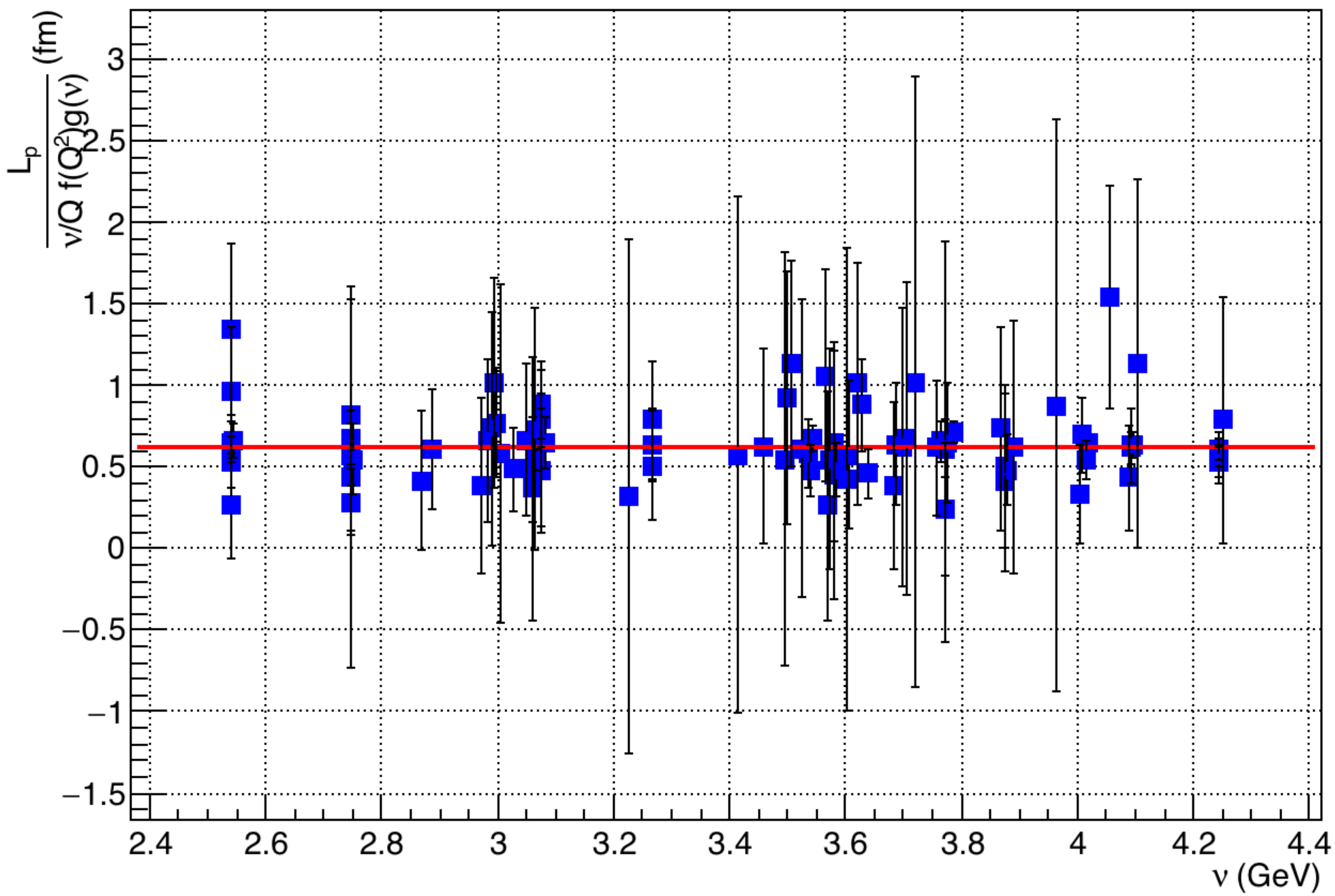
0.2<z<0.9

Additional Q^2 dependence



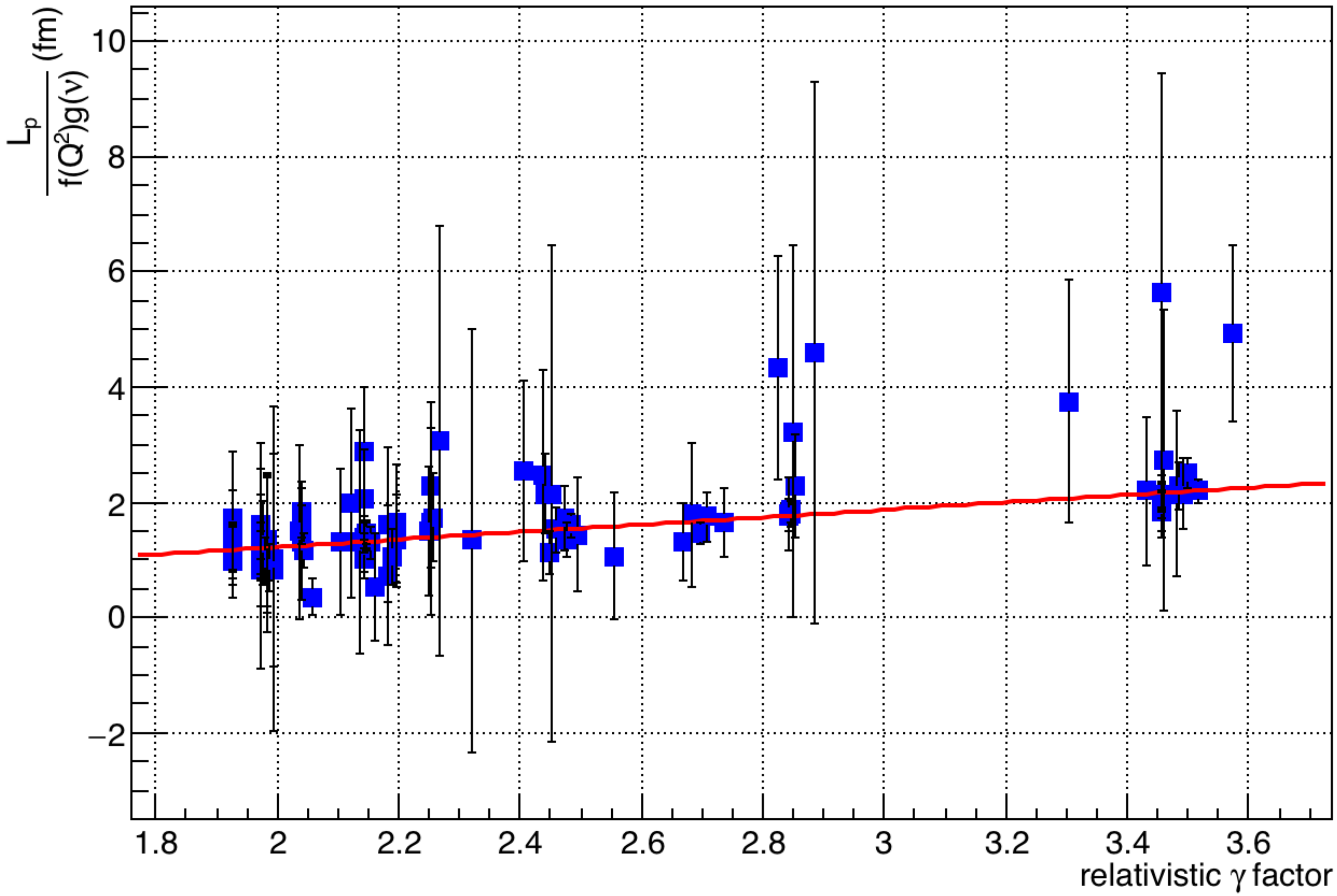
Expect some Q^2 dependence of the production length L_p in addition to the γ factor (dynamics vs. kinematics). Also observe a small ν dependence.

After removing all three factors



Distribution is flat by definition after dividing out γ factor, Q^2 dependence $f(Q^2)$, and v dependence g(v).

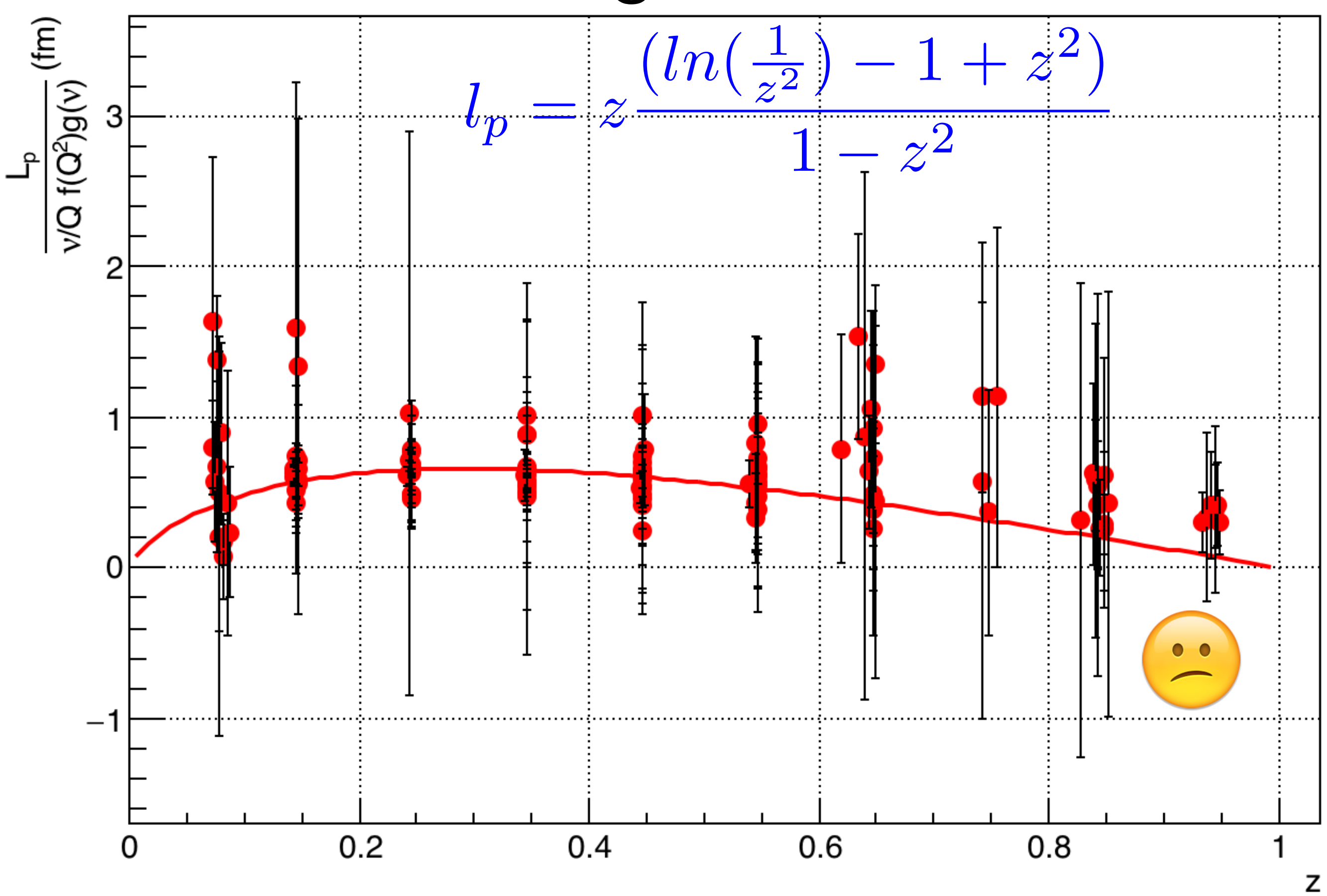
Production length vs. γ explicitly shows time dilation!



This is a strong validation of the physical picture!

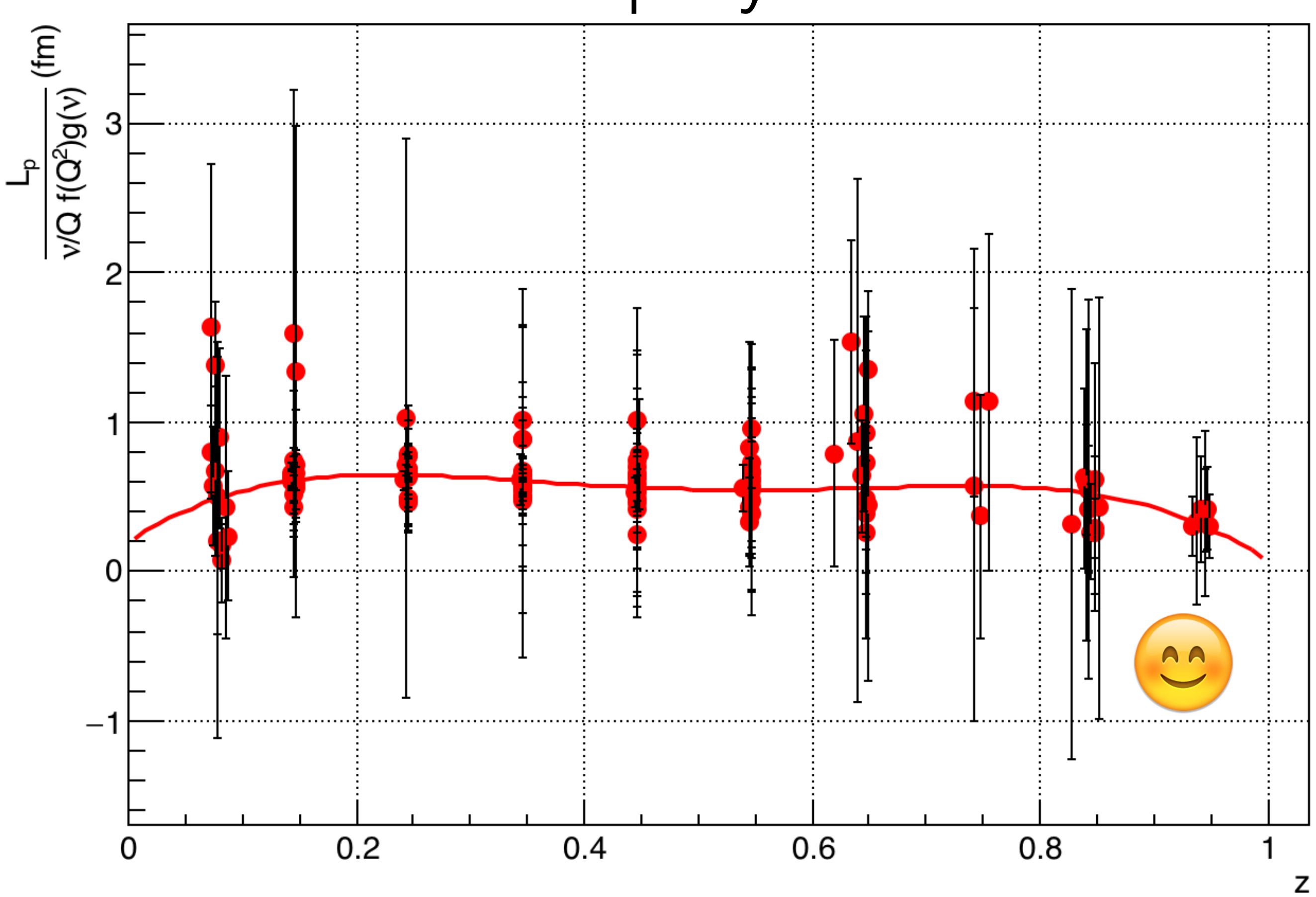
Dependence of L_p on z

Lund String Model form



String model form under-predicts L_p at high z.

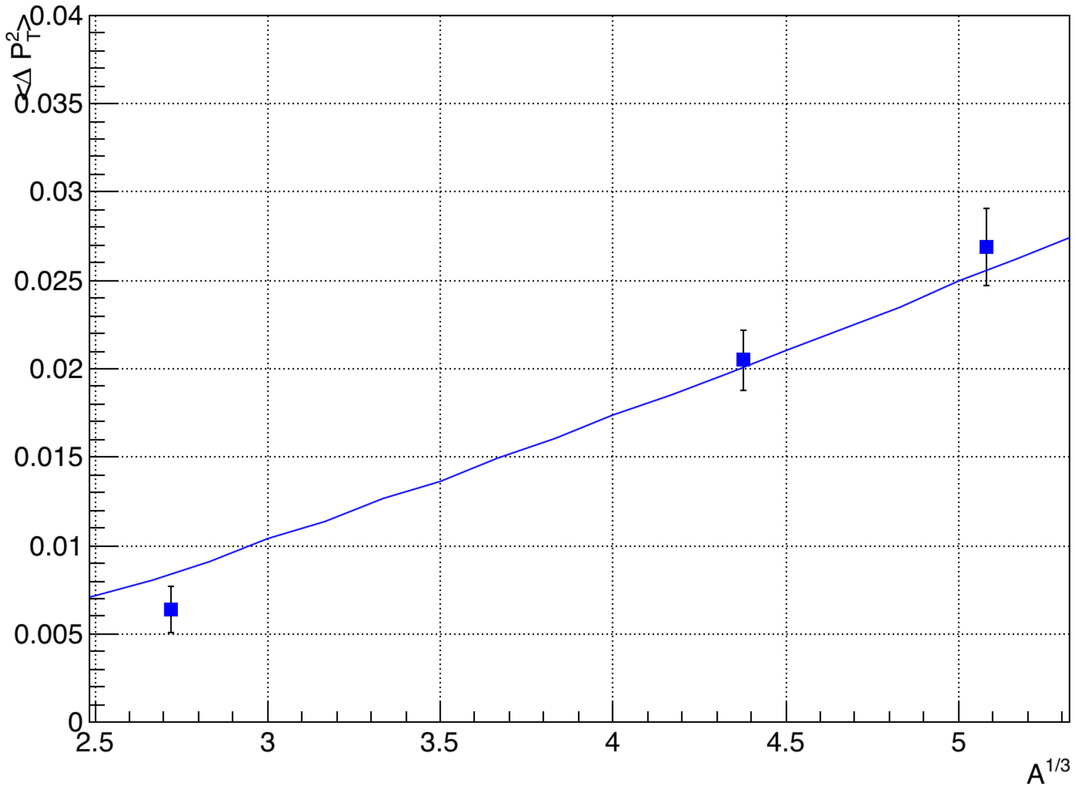
4th order polynomial



Data prefer a more symmetric shape. Trend to zero at z=1, as required by energy conservation, comes naturally out of the fit.

Note, this is the full range in z, not 0.2<z<0.9

NEW - preliminary model fits to HERMES data



$<x>=0.097$

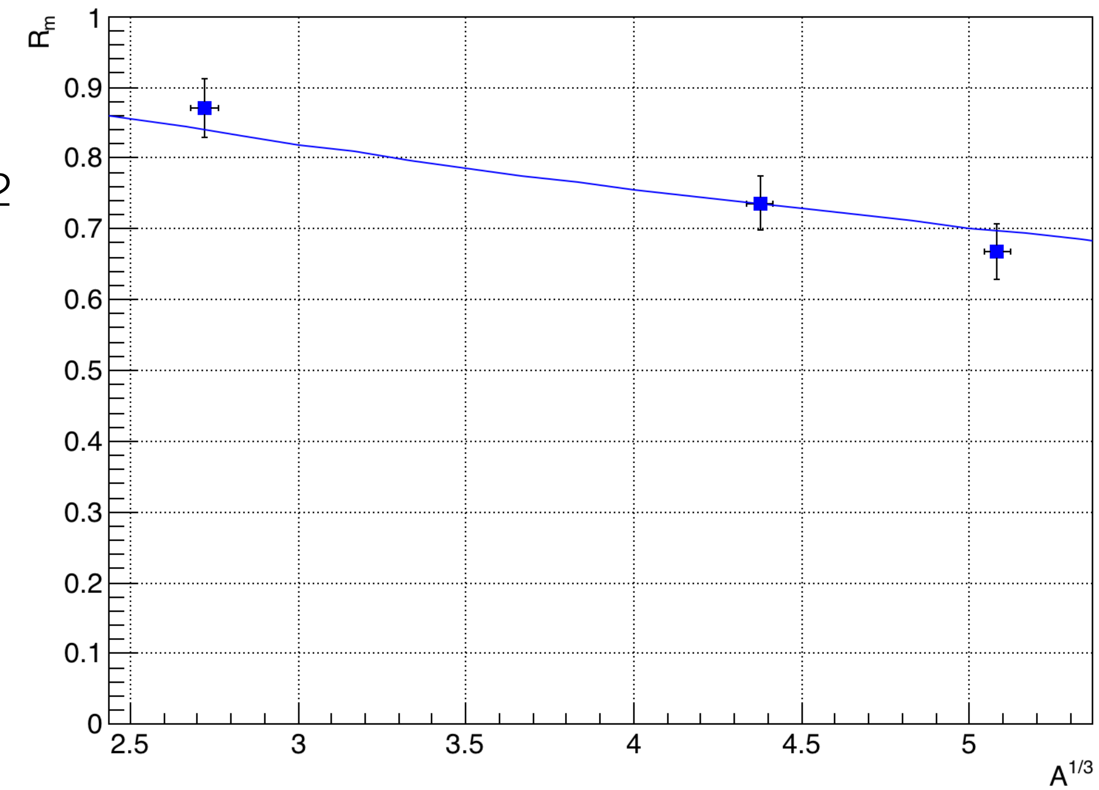
$<Q^2>=2.4\ GeV^2$

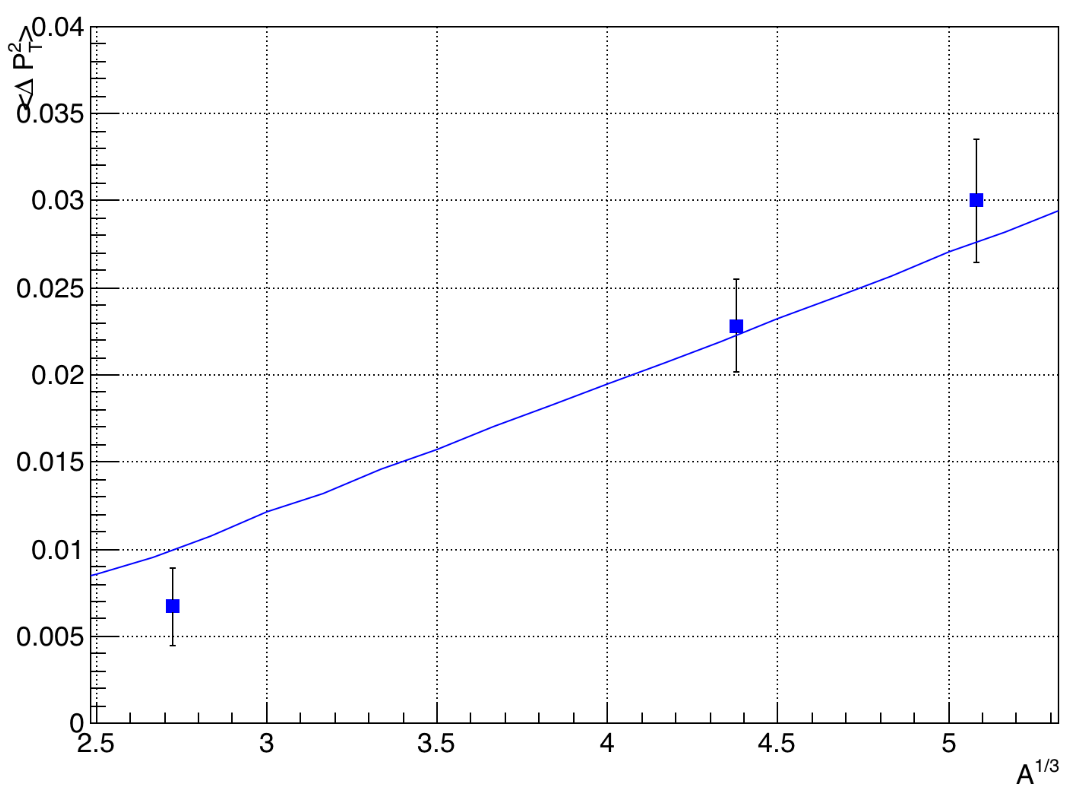
$<\nu>=14.5\ GeV$

$<z>=0.32$

L_p~10±5 fm

$\chi^2/dof = 1.3$





$<x>=0.106$

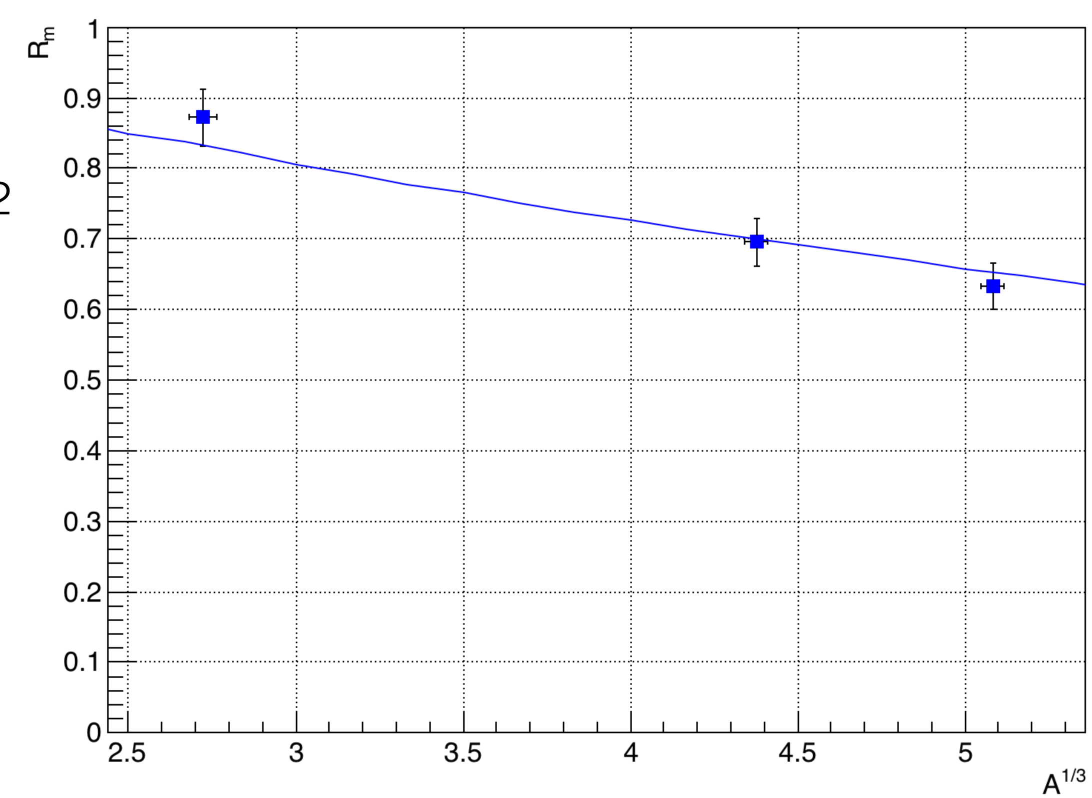
$<Q^2>=2.4\ GeV^2$

$<\nu>=13.1\ GeV$

$<z>=0.53$

L_p~7±3 fm

$\chi^2/dof = 1.3$



first fits, by Jorge López (USM)

Conclusions

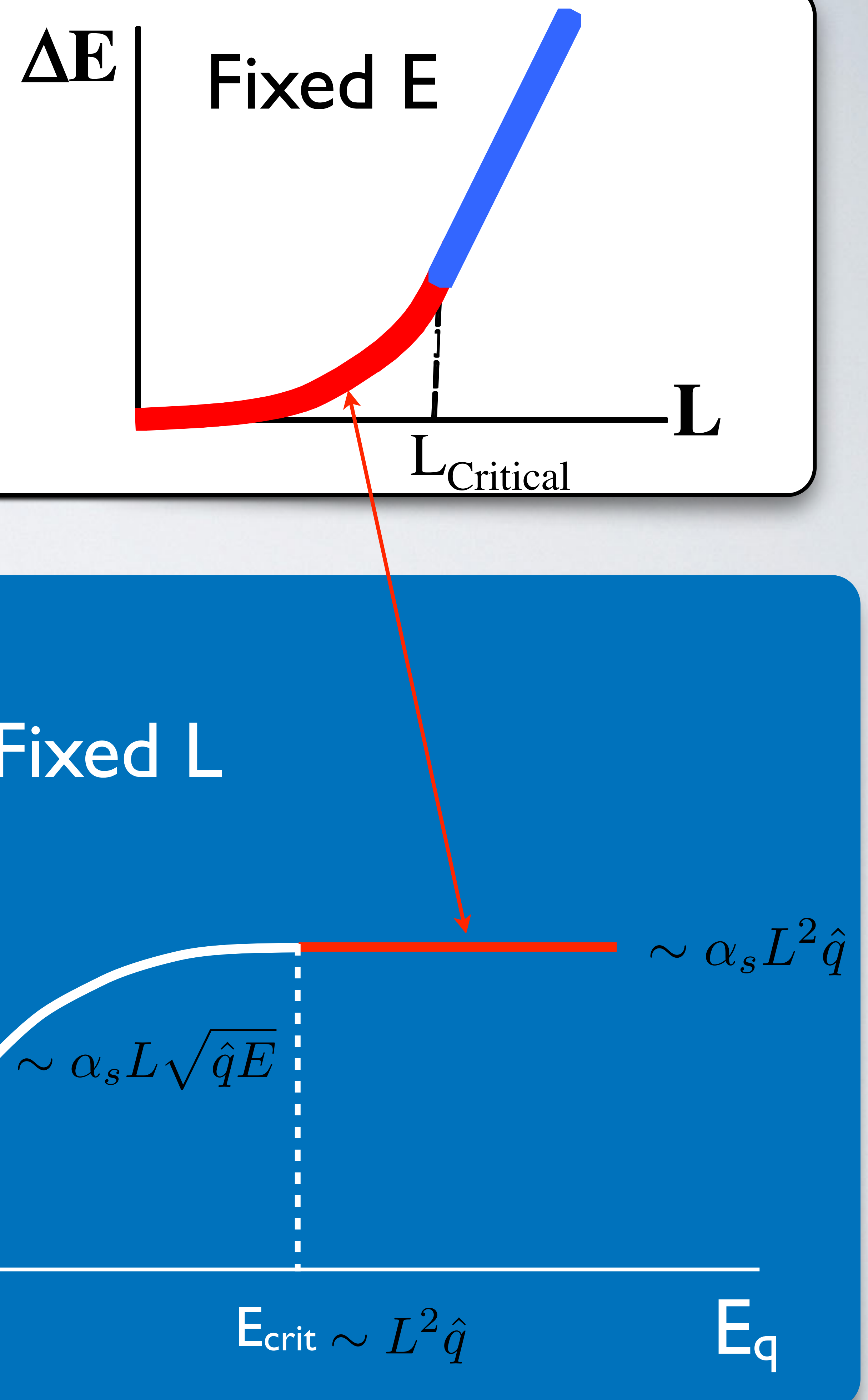
Feasibility study for production length extraction

- ➡ Excellent description of CLAS data: average of χ^2/dof<1 for 107 3-D bins in Q^2, ν, z with only 3 fit parameters
- ➡ Wide range of z, $0.2<z<0.9$: validity beyond struck quark
- ➡ Consistent with time dilation, validating physical picture
- ➡ Able to quantitatively compare z dependence with Lund String Model, and find a qualitatively different result
- ➡ Exploratory: $<L_p>=0.65\pm0.02*(\nu/Q)$ fm, average 1.7 fm
- ➡ First look at applying this model to HERMES data

Additional slides

$L < L_{Critical}$ $\quad -\frac{dE}{dx} \propto L\hat{q}$

$L > L_{Critical}$ $\quad -\frac{dE}{dx} \propto \sqrt{E\hat{q}}$



Partonic energy loss in pQCD (BDMPS-Z) exhibits a critical system length L_c and a critical energy E_c

$$L_c \propto \sqrt{\frac{E_q}{\hat{q}}}$$

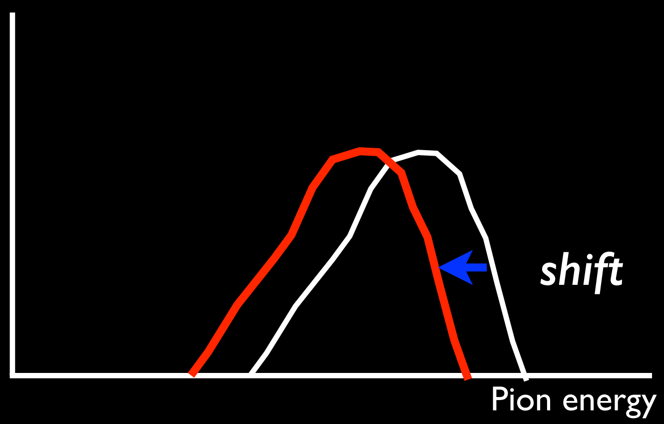
$$E_c \approx 0.4 \cdot \left(\frac{L}{1\ \mathrm{fm}}\right)^2\ \mathrm{GeV}$$

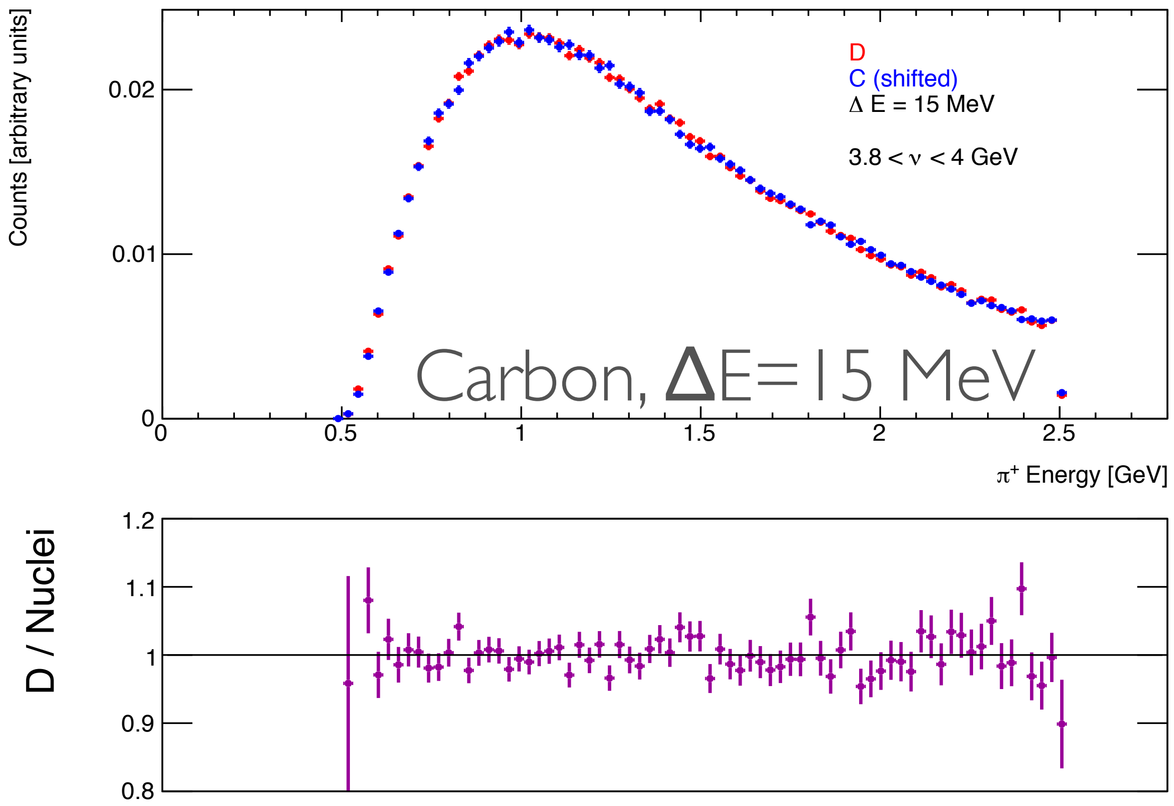
Exploring a direct measurement of quark energy loss

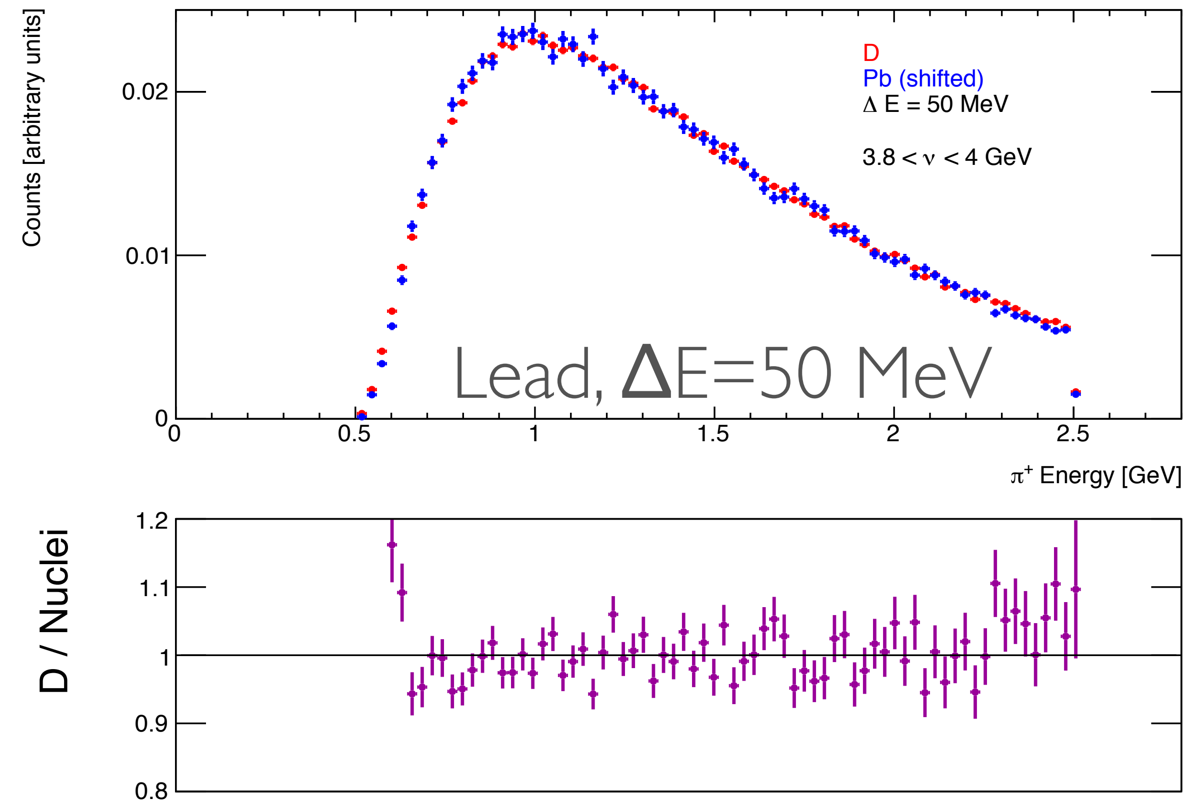
Miguel Arratia, Cristian Peña,
Hayk Hakobyan, Sebastian Tapia,
Oscar Aravena, WB

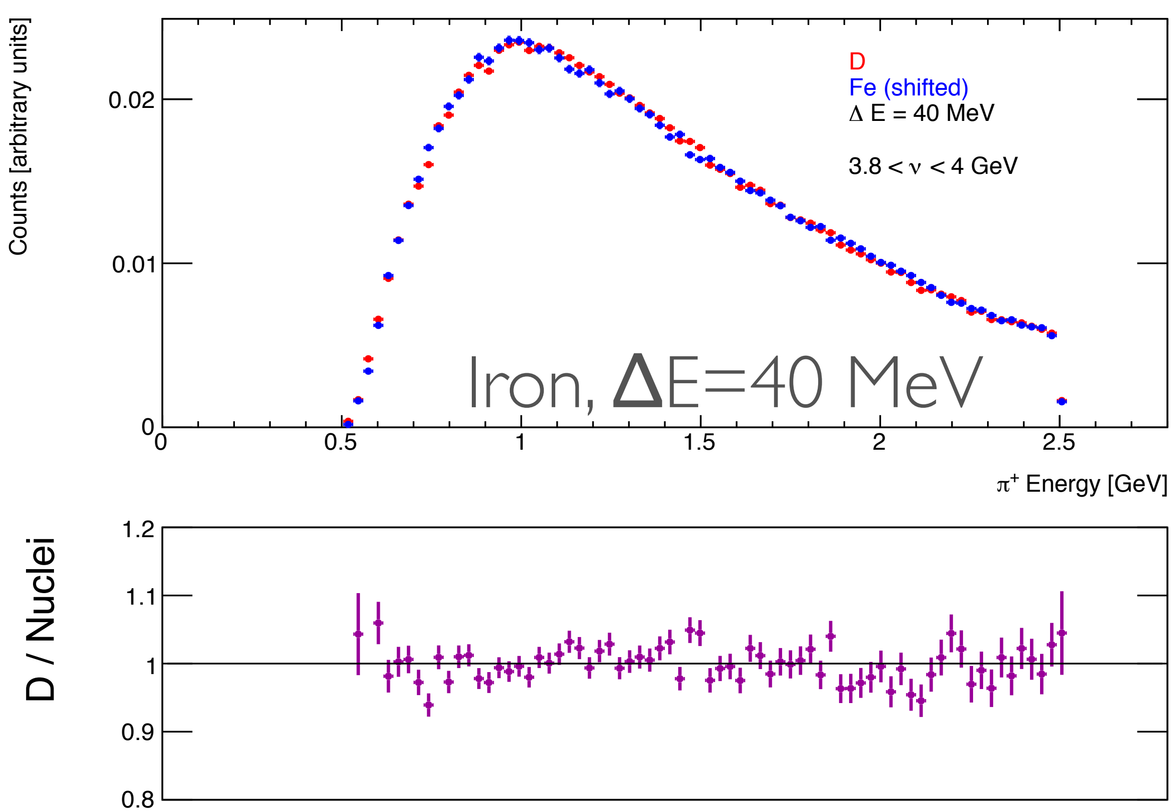
How to *directly* measure quark energy loss?

- Energy loss is predicted on very solid grounds to be *independent of energy* for a medium that is thin enough.
- "Thin enough" depends on energy, see earlier slide; if medium is thicker than "thin enough" it still loses energy
- If the energy loss is independent of energy, it will produce a ***shift*** of the energy spectrum, for higher energies.
- We can look for a ***shift*** of the Pb energy spectrum compared to that of the deuterium energy spectrum





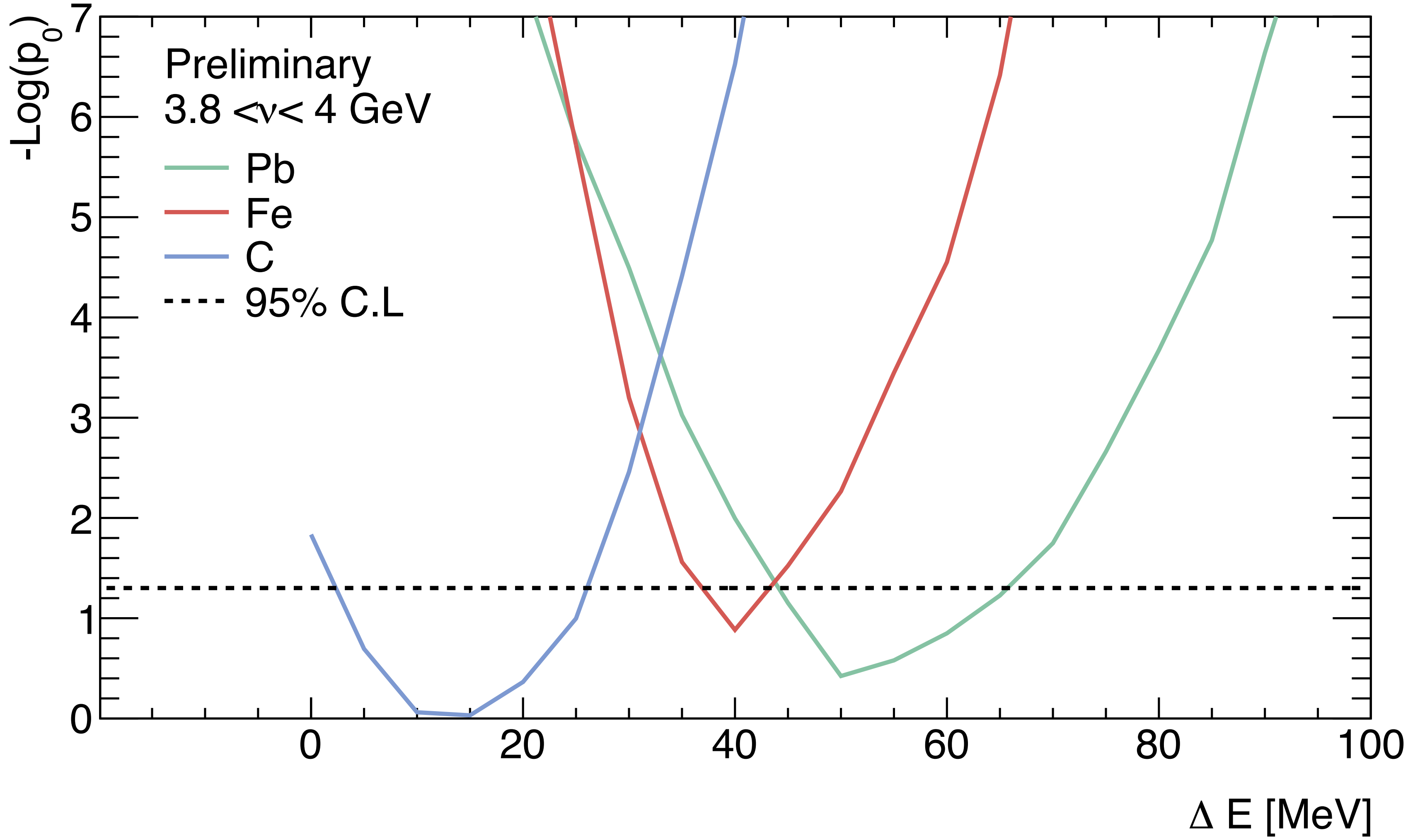




Energy spectrum of π^+ produced in C, Fe, Pb compared to that of deuterium, normalized to unity, with energy shifted by ΔE.

Acceptance corrected
Cut on $X_F > 0.1$ is applied

Consistent with simple energy shift + unchanged fragmentation

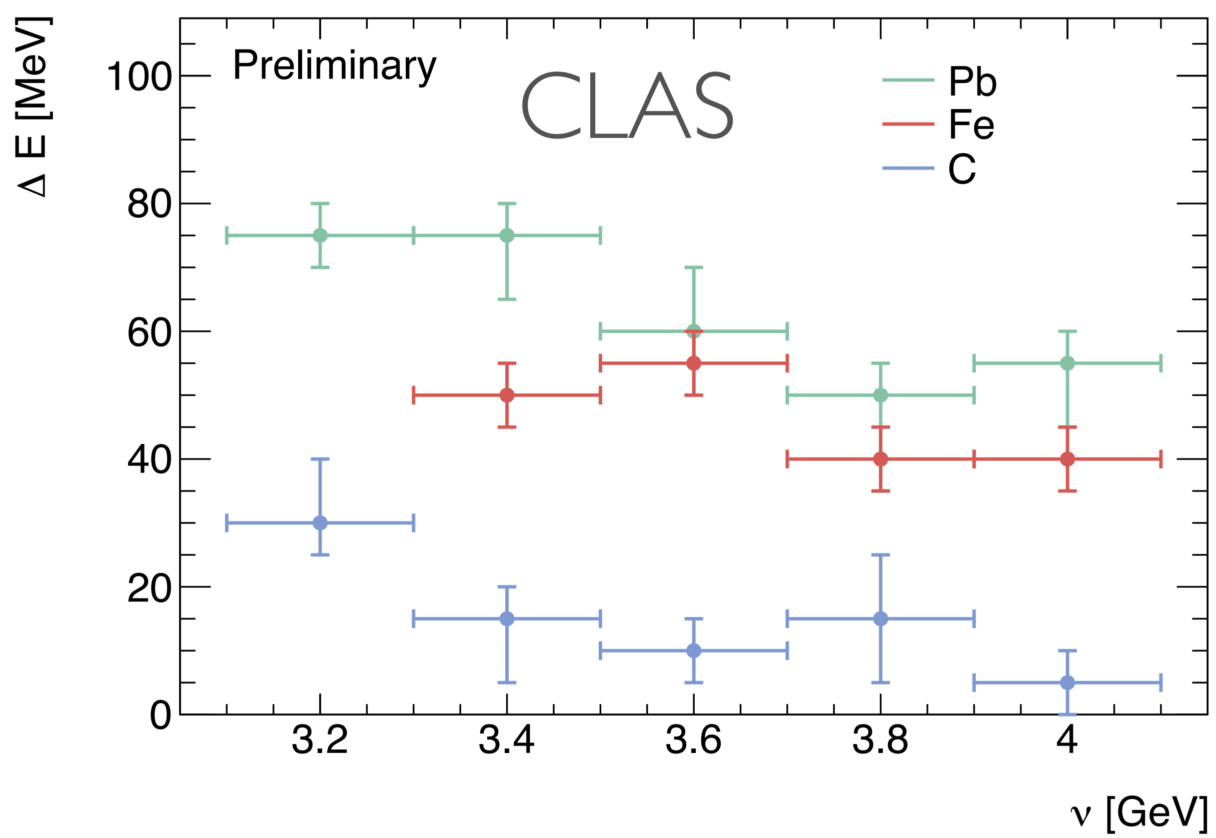


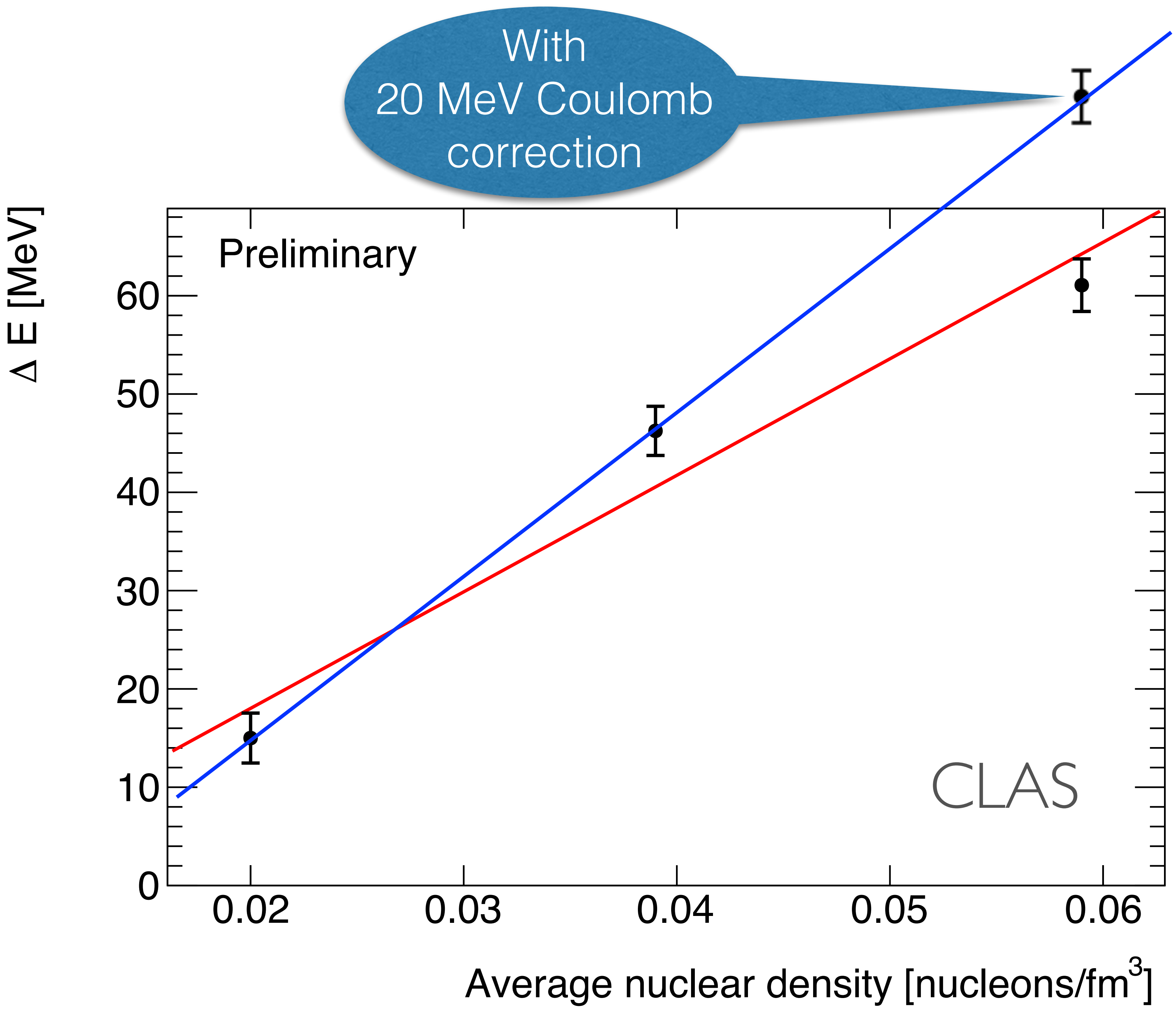
Log of p-values of Kolmogorov-Smirnov test as a function of energy shift ΔE: carbon, iron, lead.

Dashed line corresponds to 95% confidence level

ν/GeV	Carbon	Iron	Lead
2.4–2.6	—	—	—
2.6–2.8	—	—	—
2.8–3.0	—	—	—
3.0–3.2	—	—	—
3.2–3.4	20–35	—	75
3.4–3.6	10–25	50	70–85
3.6–3.8	10–25	55	50–70
3.8–4.0	5–25	40	45–65
4.0–4.2	5–10	35-40	50–65

Range of possible energy shift in MeV obtained by Kolmogorov-Smirnov test in **ν** intervals





Approximately proportional to density, as expected.
(fixed pathlength)
Supports the premise that what we measure is ~energy loss!

NEW THEORY DEVELOPMENT

- T. Liou, A.H. Mueller, B. Wu: Nuclear Physics A 916 (2013) 102–125, arXiv:1304.7677

  - *Old*: multiple scattering → gluon emission, = energy loss

$$-\frac{dE}{dx} = \frac{\alpha_s N_c}{4} \Delta p_T^2 \ \propto \ \hat{q}\ L$$

  - *New*: this energy loss creates *more* p_T broadening

$$\Delta p_T^2 = \frac{\alpha_s N_c}{8\pi}\ \hat{q}\ L \boxed{ln^2 \frac{L^2}{l_0^2}} + \ldots.$$

→ predicts a non-linear relationship between p_T broadening and L.

DIS channels: *stable* hadrons, accessible with 11 GeV JLab future experiment PR12-06-117

Actively underway with existing 5 GeV data

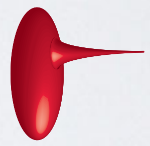
HERMES

meson	$c\tau$	mass	flavor content
π^0	25 nm	0.13	ud
π^+, π^-	7.8 m	0.14	ud
η	170 pm	0.55	uds
ω	23 fm	0.78	uds
η'	0.98 pm	0.96	uds
φ	44 fm	1	uds
f1	8 fm	1.3	uds
K^0	27 mm	0.5	ds
K^+, K^-	3.7 m	0.49	us

baryon	$c\tau$	mass	flavor content
p	stable	0.94	ud
$\bar{p}$	stable	0.94	ud
Λ	79 mm	1.1	uds
$\Lambda(1520)$	13 fm	1.5	uds
Σ^+	24 mm	1.2	us
Σ^-	44 mm	1.2	ds
Σ^0	22 pm	1.2	uds
Ξ^0	87 mm	1.3	us
Ξ^-	49 mm	1.3	ds

ADDITIONAL IMPORTANT STUDIES: DIS

- Jets
- Di-hadron attenuation (hadronization mechanisms)
- Photon-hadron correlations
- Bose-Einstein correlations
- Correlated low-energy particles
- Target fragmentation, and target-current correlations



Proton minus one quark

- Single and double spin asymmetries in meson production from nuclei
- Color transparency

Model description IV:
4-parameter and 5-parameter versions

4-parameter: add z shift Δz due to partonic energy loss to multiplicity ratio fit.

5-parameter: change pT broadening expression from

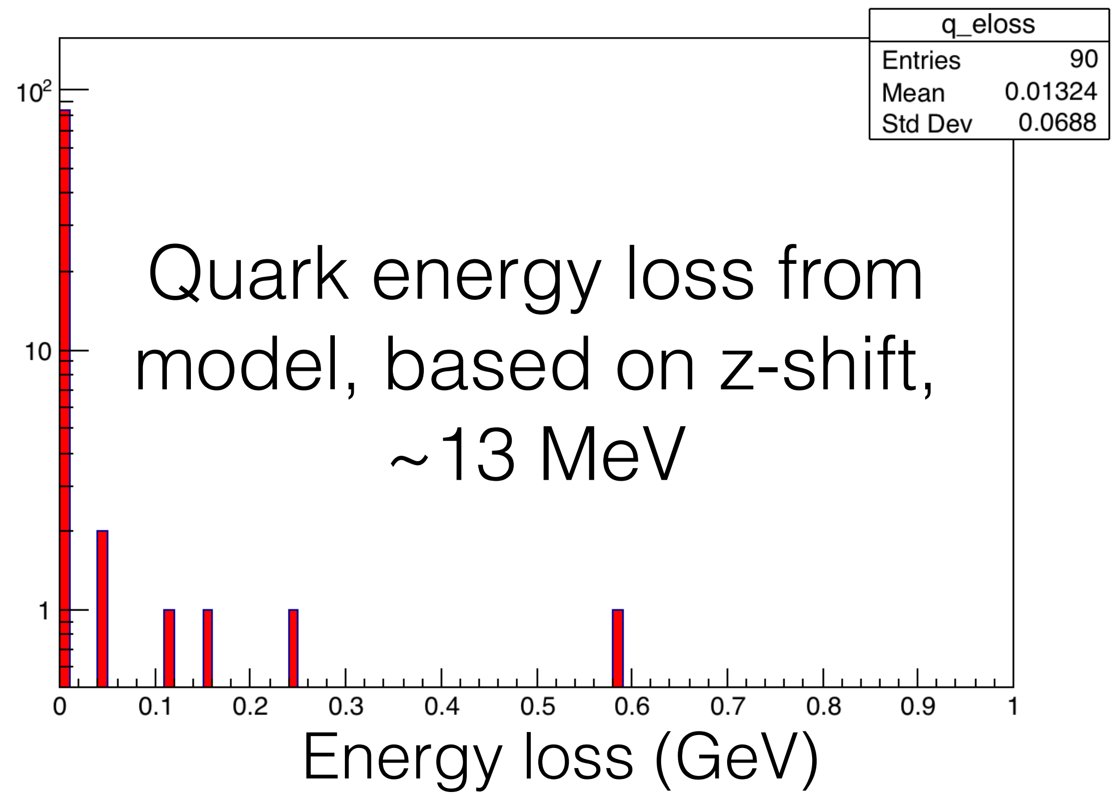
$$\langle \Delta p_T^2 \rangle_L = \hat{q}_0 \cdot L$$

to

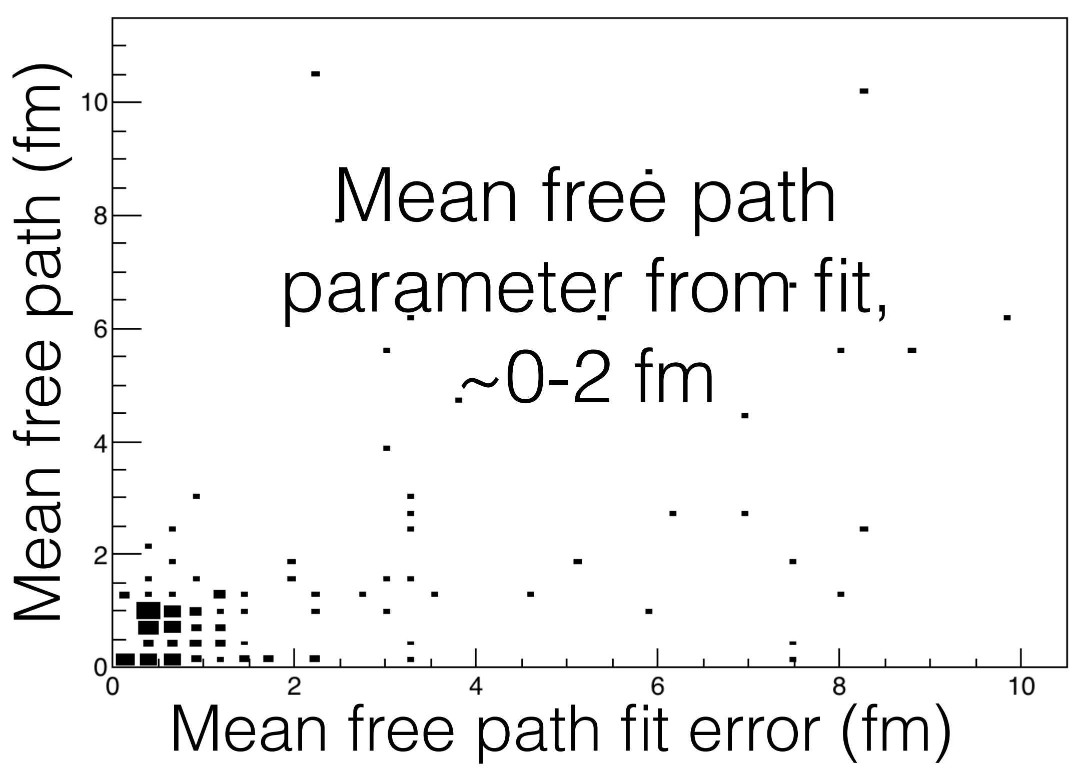
$$\langle \Delta p_T^2 \rangle_L = \hat{q}_0 \cdot L \cdot ln^2(\frac{L^2}{l_0^2})$$

which contains mean free path parameter ℓ_0

Parameters from 4-parameter and 5-parameter model fits



Has z cut and eliminates ultra-high q-hat bins. (Assumes same z shift for all nuclei, as an approximation.) Order of magnitude of the mean value agrees with direct measurement of energy loss, but uncertainties are large.

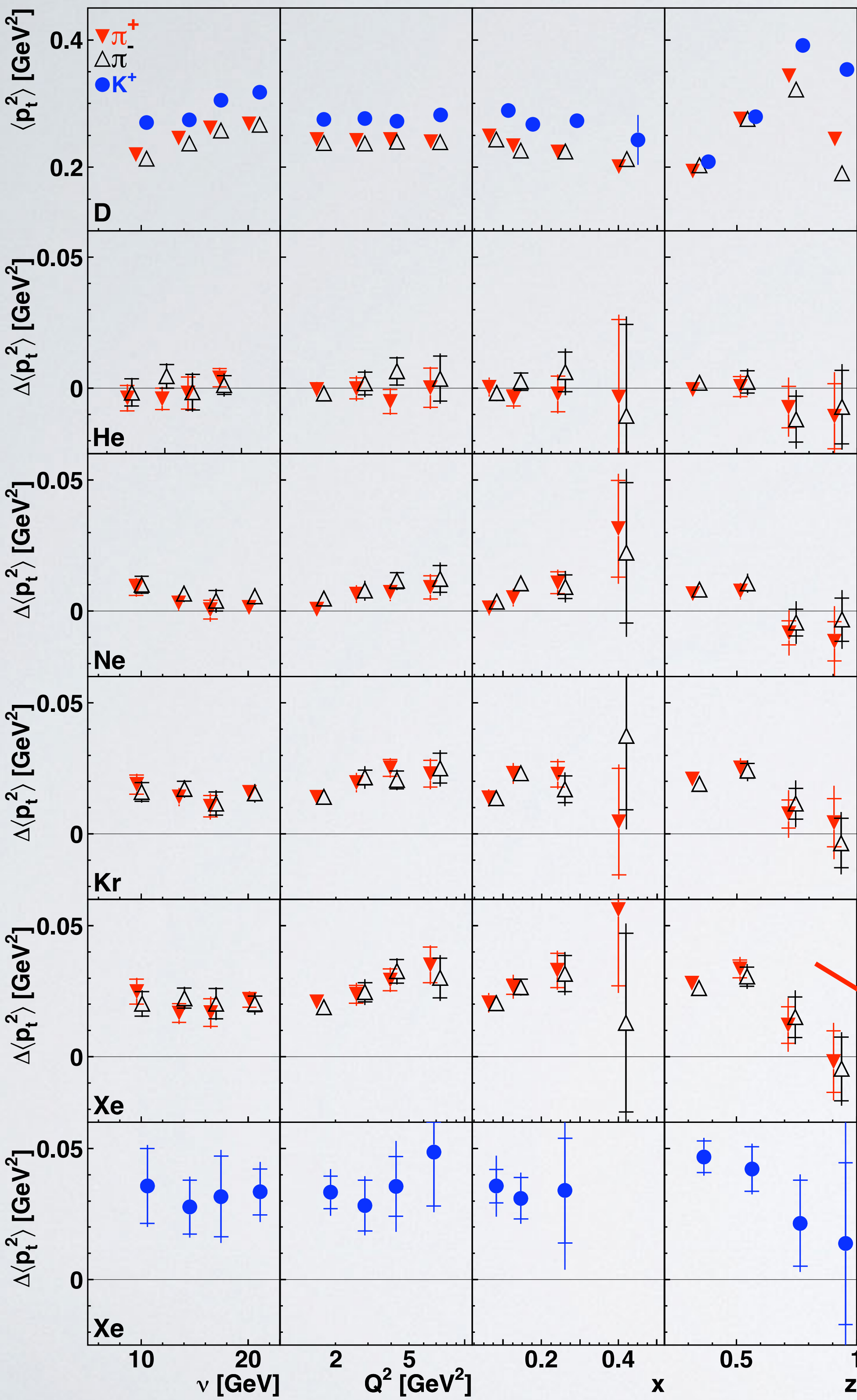


Mean free path parameter from 5-parameter model vs. its fit error, for fit errors < 10 fm; 128 bins.

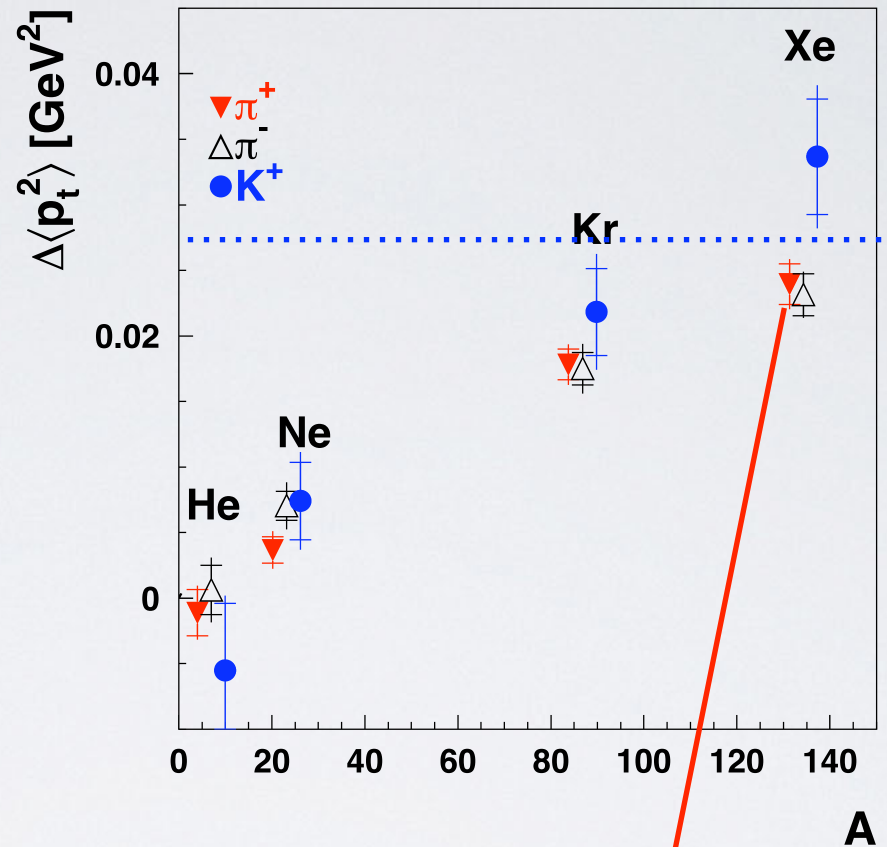
P_T BROADENING FROM HERMES

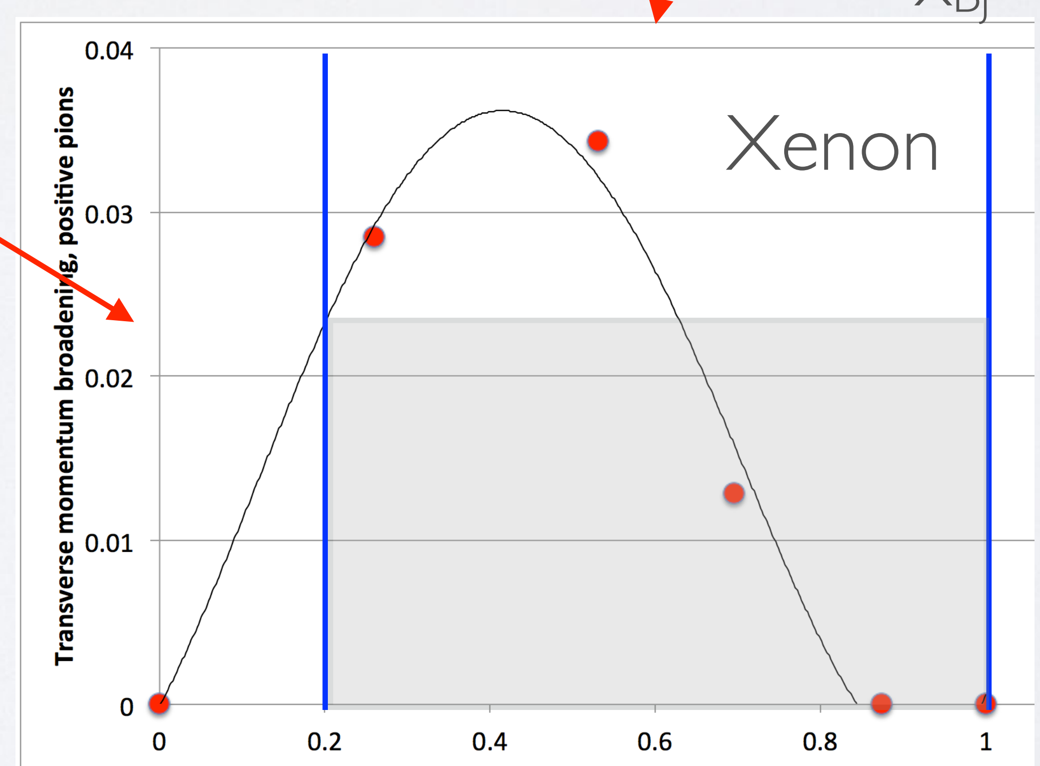
Q: Why is CLAS broadening larger than HERMES broadening?

A: Averaging over z results in reduced broadening. CLAS results binned in ν, Q^2, z. (Fermi motion small, suppressed by a factor of $\{z \cdot x_{Bj}\}^2$). Also, they extend well below x_{Bj}=0.1: $q\bar{q}$ pairs



1-D distributions, integrated over all other variables





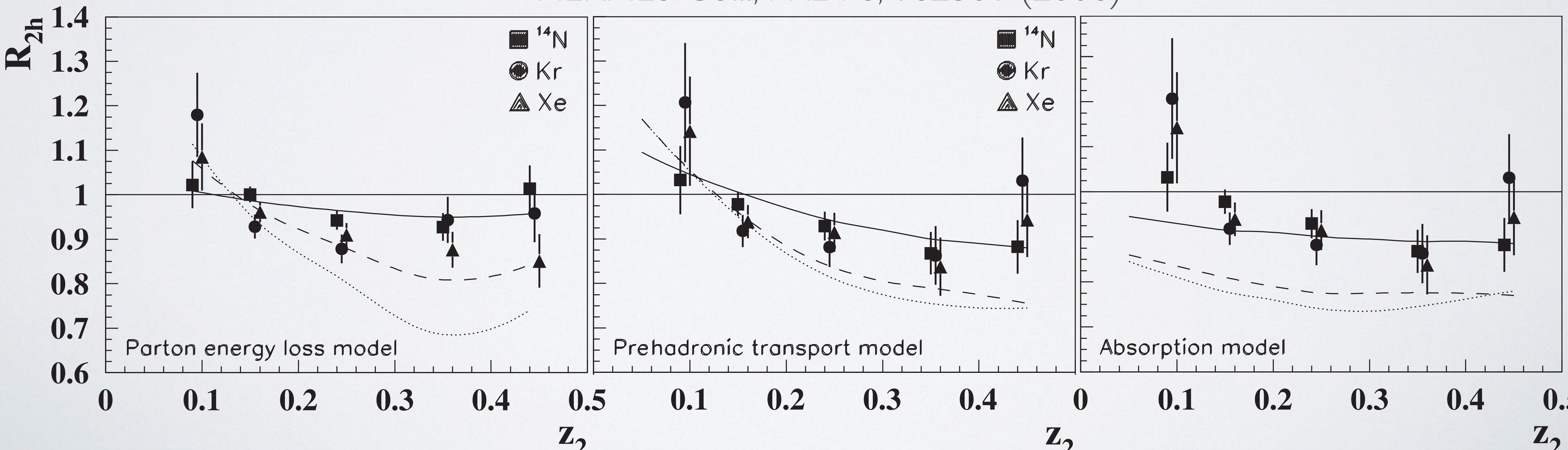
DOUBLE MULTIPLICITY RATIOS

$$R_{2h}(z_2) = \frac{\left(\frac{dN^{z_1>0.5}(z_2)/dz_2}{N^{z>0.5}}\right)_A}{\left(\frac{dN^{z_1>0.5}(z_2)/dz_2}{N^{z>0.5}}\right)_D}$$

- Choose events with 2 hadrons
- Leading hadron has z_1, subleading z_2
- Normalize to number of events with at least one hadron with z>0.5

→ sensitive to hadronization mechanism!

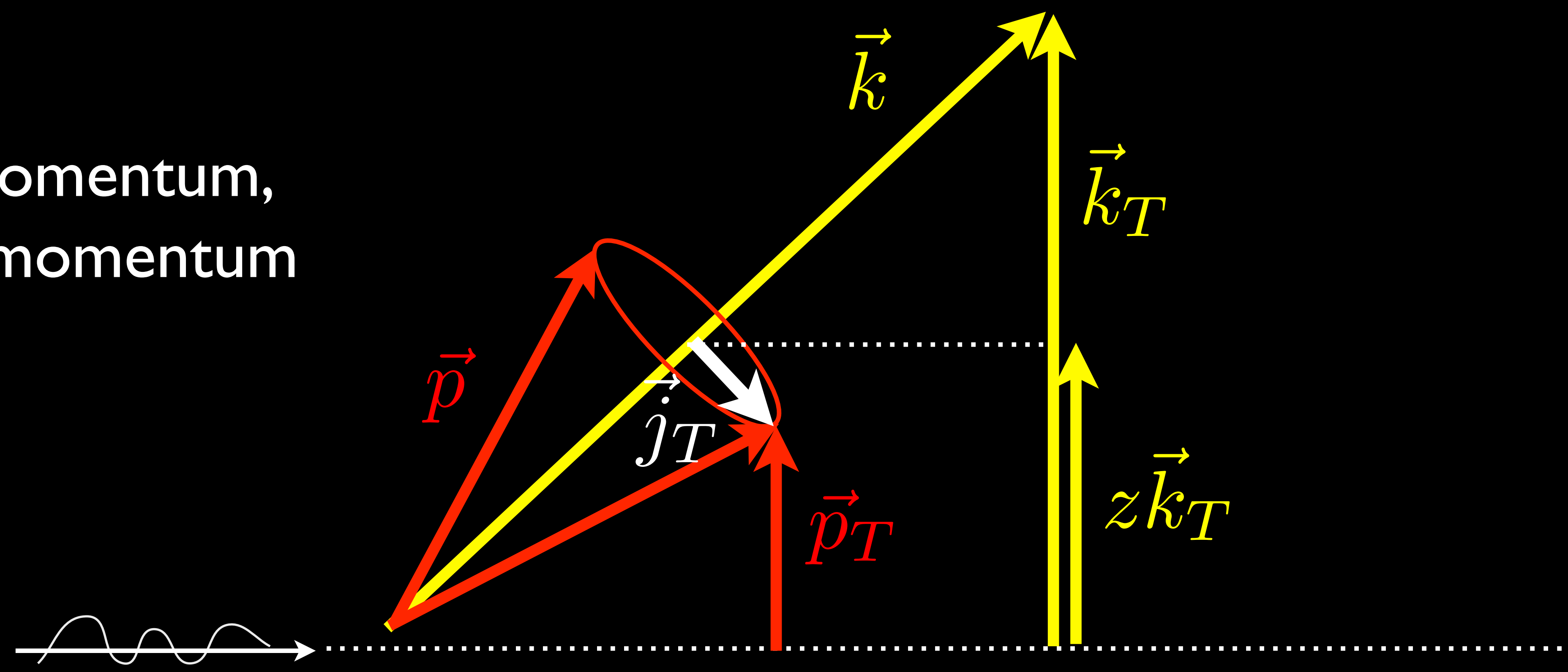
HERMES Coll., PRL 96, 162301 (2006)



Quark k_T broadening vs. *hadron* p_T broadening

The k_T broadening experienced by a quark is "*diluted*" in the fragmention process

k is the ***quark*** momentum,
p is the ***hadron*** momentum



$$\vec{p}_T = z\vec{k}_T + \vec{j}_T$$

$$\langle p_T^2 \rangle = \langle z^2 k_T^2 \rangle + \langle j_T^2 \rangle$$

$$\Delta\langle p_T^2 \rangle = \Delta\langle z^2 k_T^2 \rangle + \Delta\langle j_T^2 \rangle$$

~0

$$\boxed{\Delta\langle p_T^2 \rangle \approx z^2 \Delta\langle k_T^2 \rangle}$$

Verified for pions to 5-10% accuracy for vacuum case, z=0.4-0.7, by Monte Carlo studies

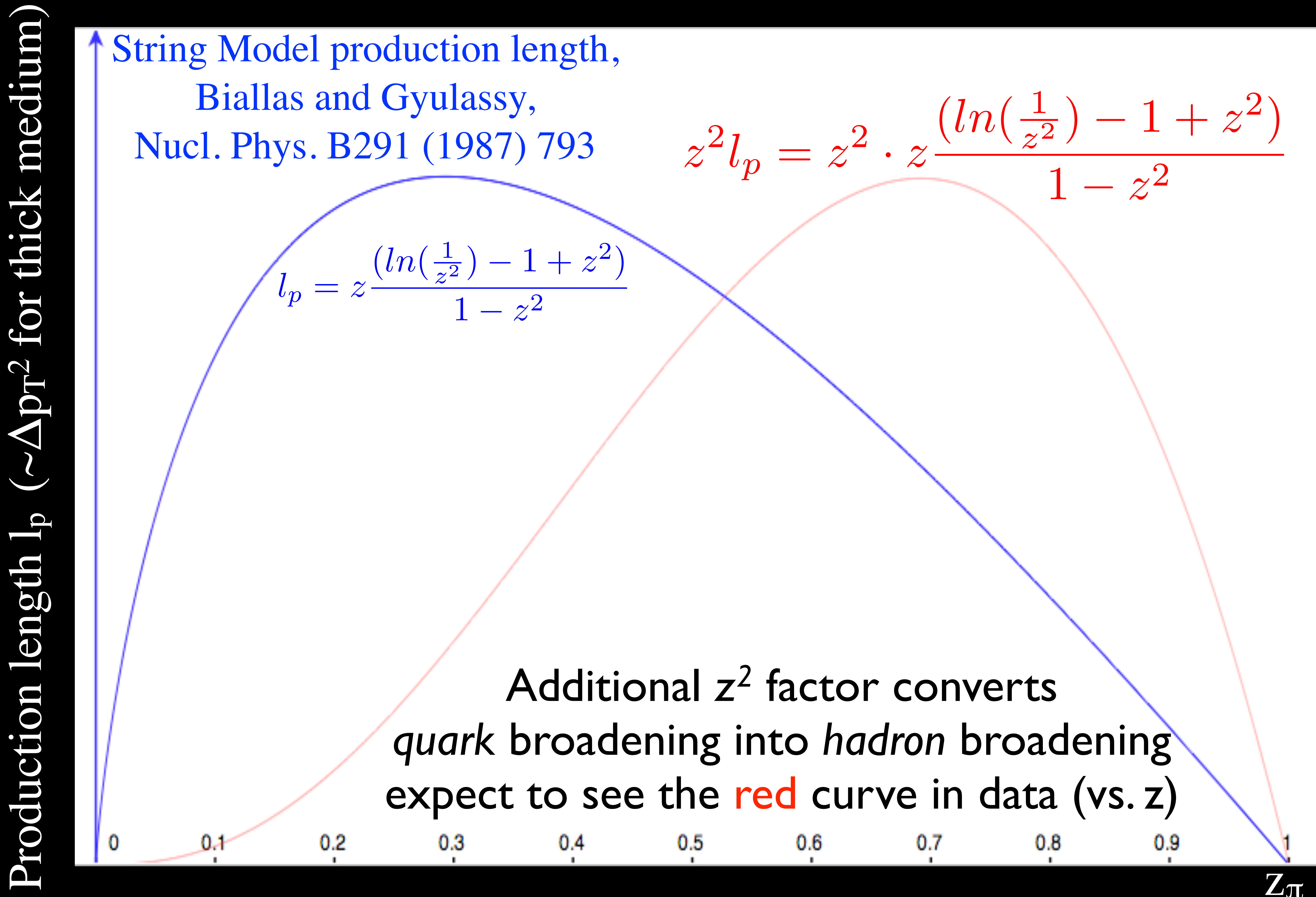
Basic questions at low energies:

Partonic processes dominate, or hadronic? in which kinematic regime? classical or quantum?

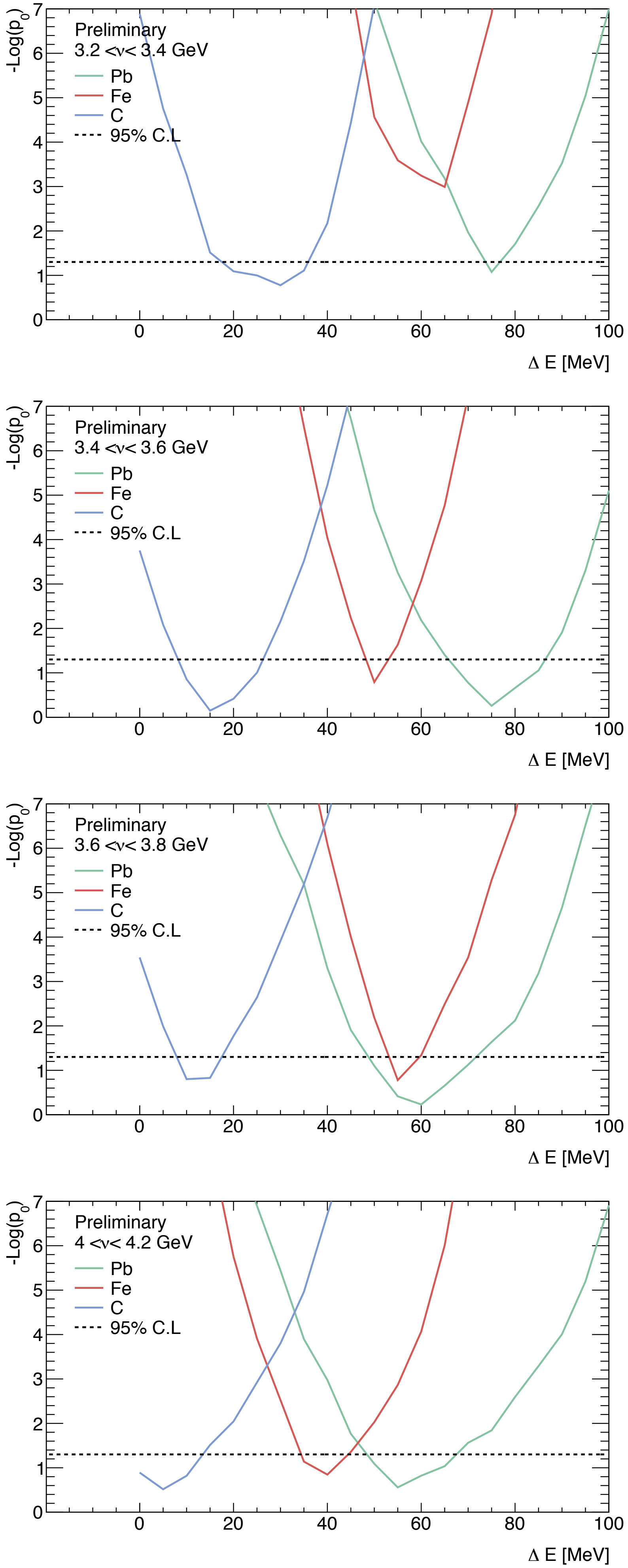
Can identify dominant hadronization mechanisms, uniquely? what are the roles of flavor and mass?

What can we infer about fundamental QCD processes by observing the interaction with the nucleus?

If p_T broadening uniquely signals the partonic stage, can use this as one tool to answer these questions

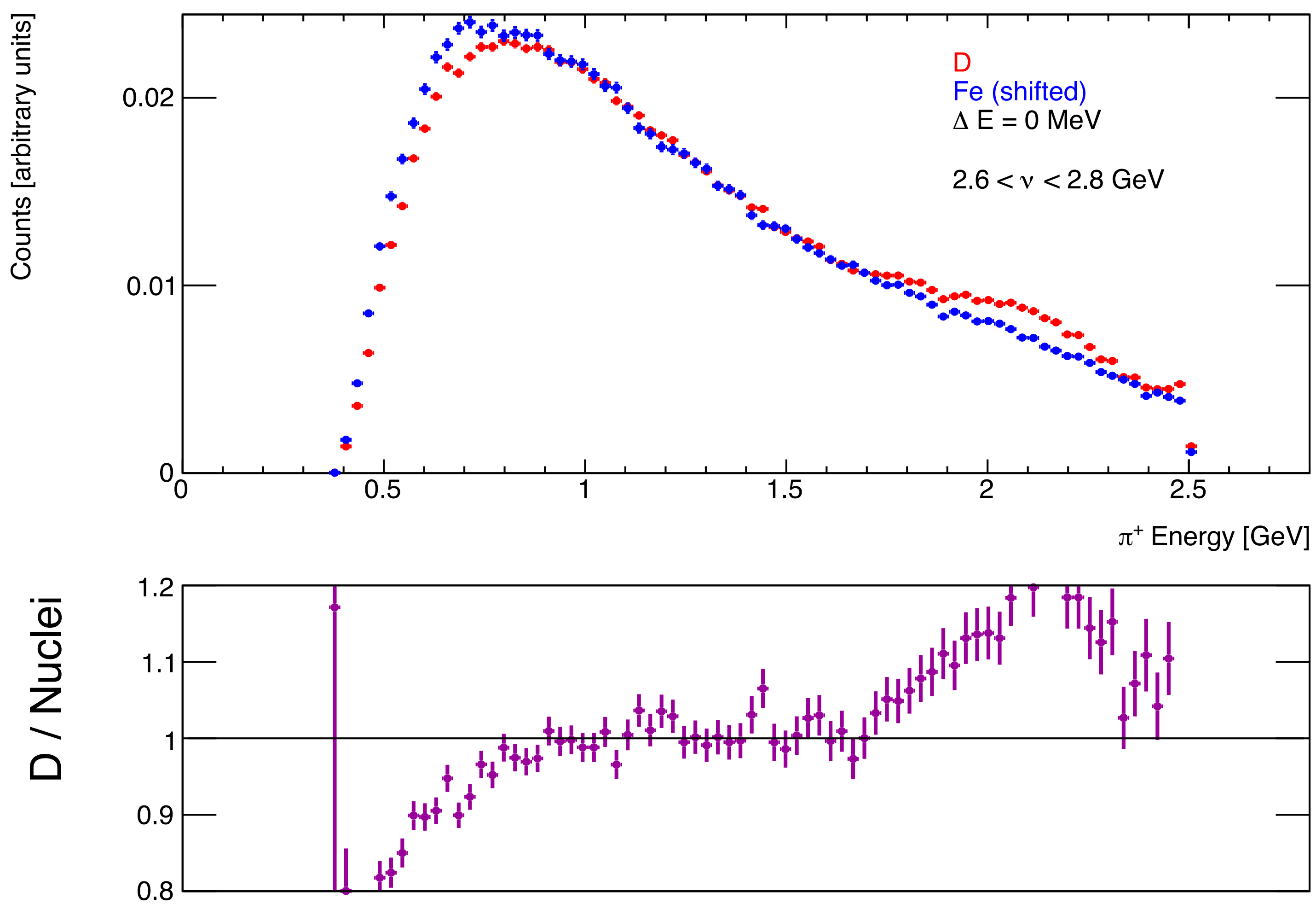


String Model production length,
Biallas and Gyulassy,
Nucl. Phys. B291 (1987) 793
$z^2 l_p = z^2 \cdot z \frac{(ln(\frac{1}{z^2}) - 1 + z^2)}{1 - z^2}$
$l_p = z \frac{(ln(\frac{1}{z^2}) - 1 + z^2)}{1 - z^2}$
Additional z^2 factor converts
quark broadening into *hadron* broadening
expect to see the red curve in data (vs. z)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
z_π
Production length l_p ($\sim\Delta p_T^2$ for thick medium)

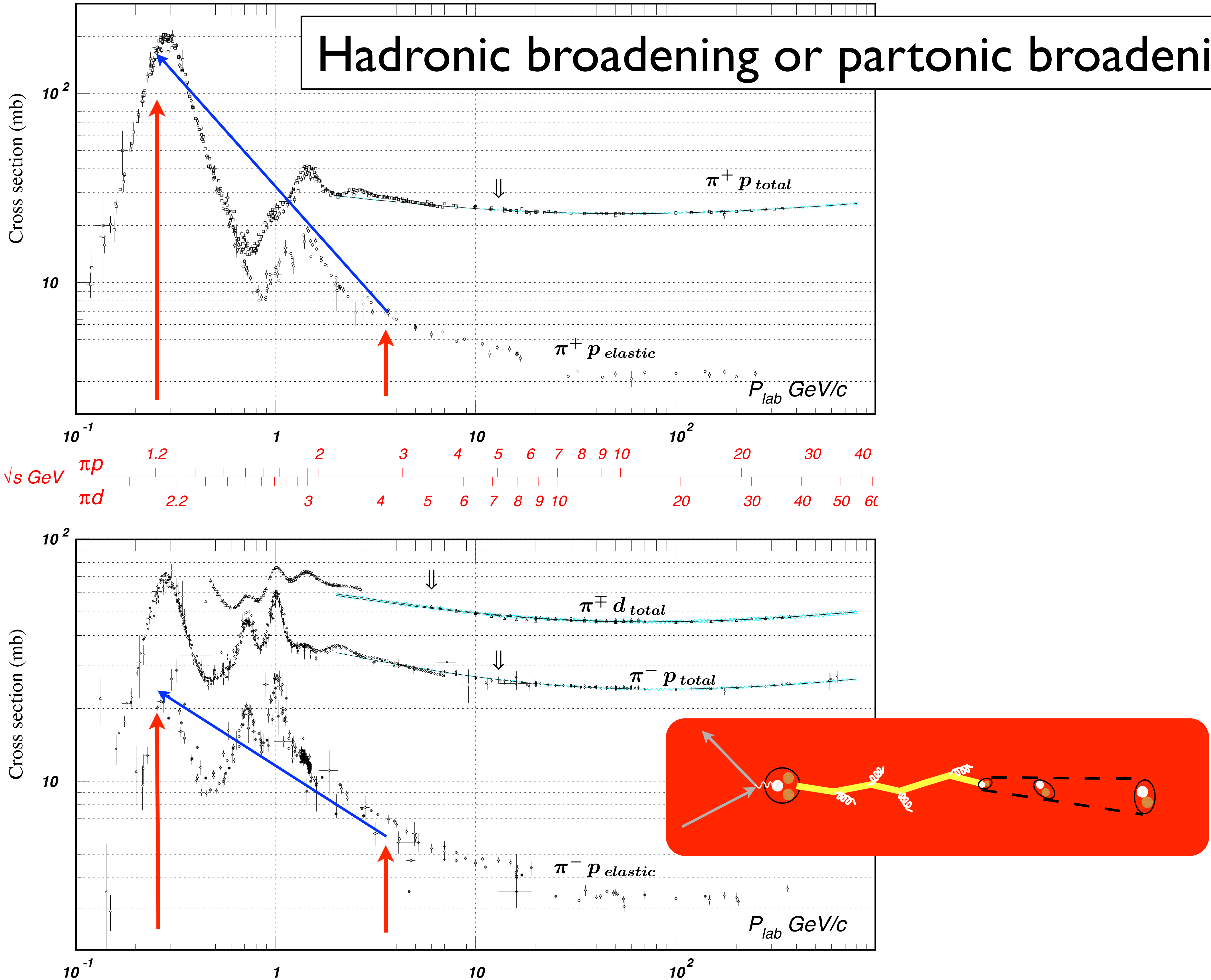


Pattern seen as a function of increasing ν

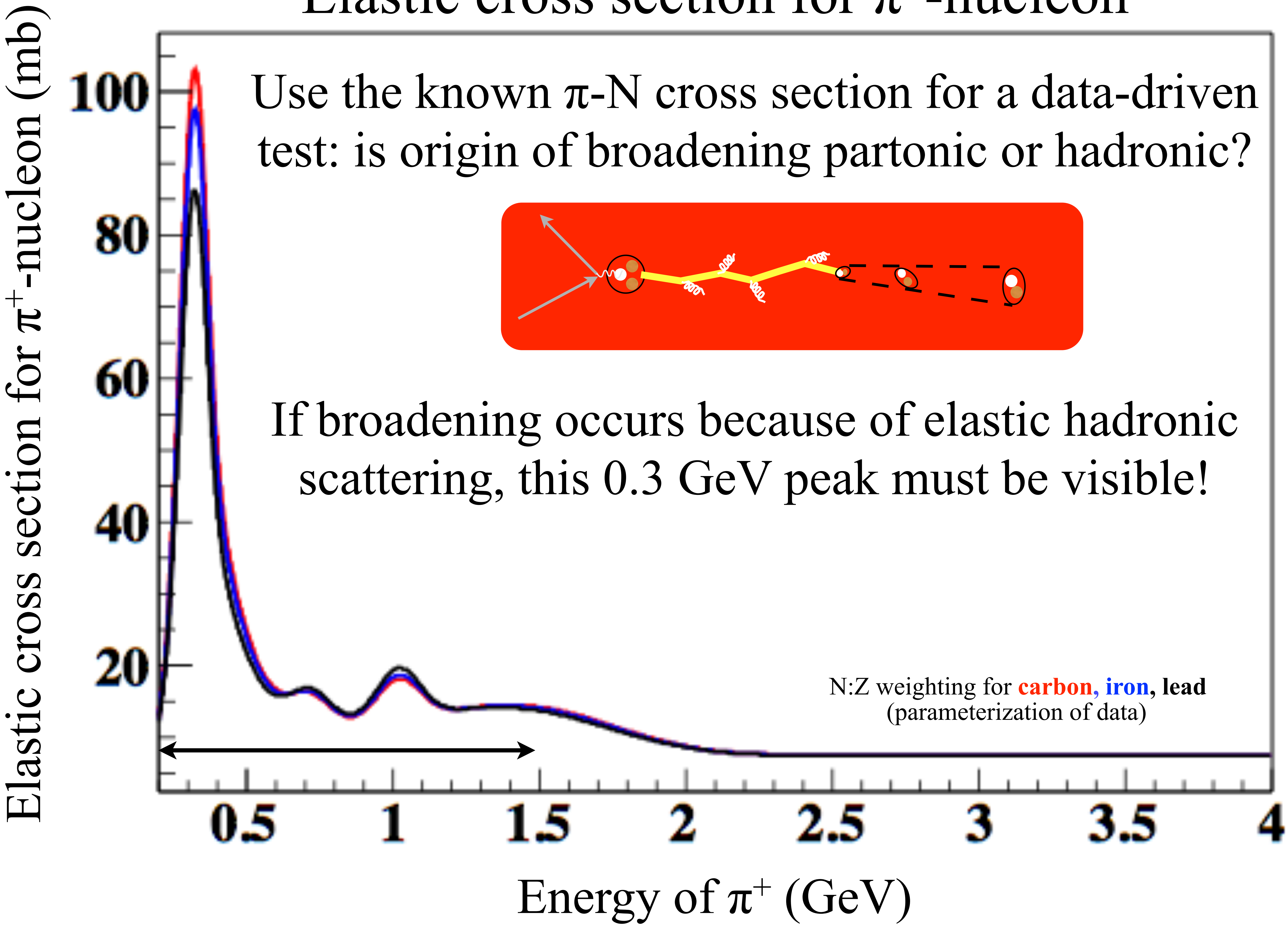
What happens if ν is too low



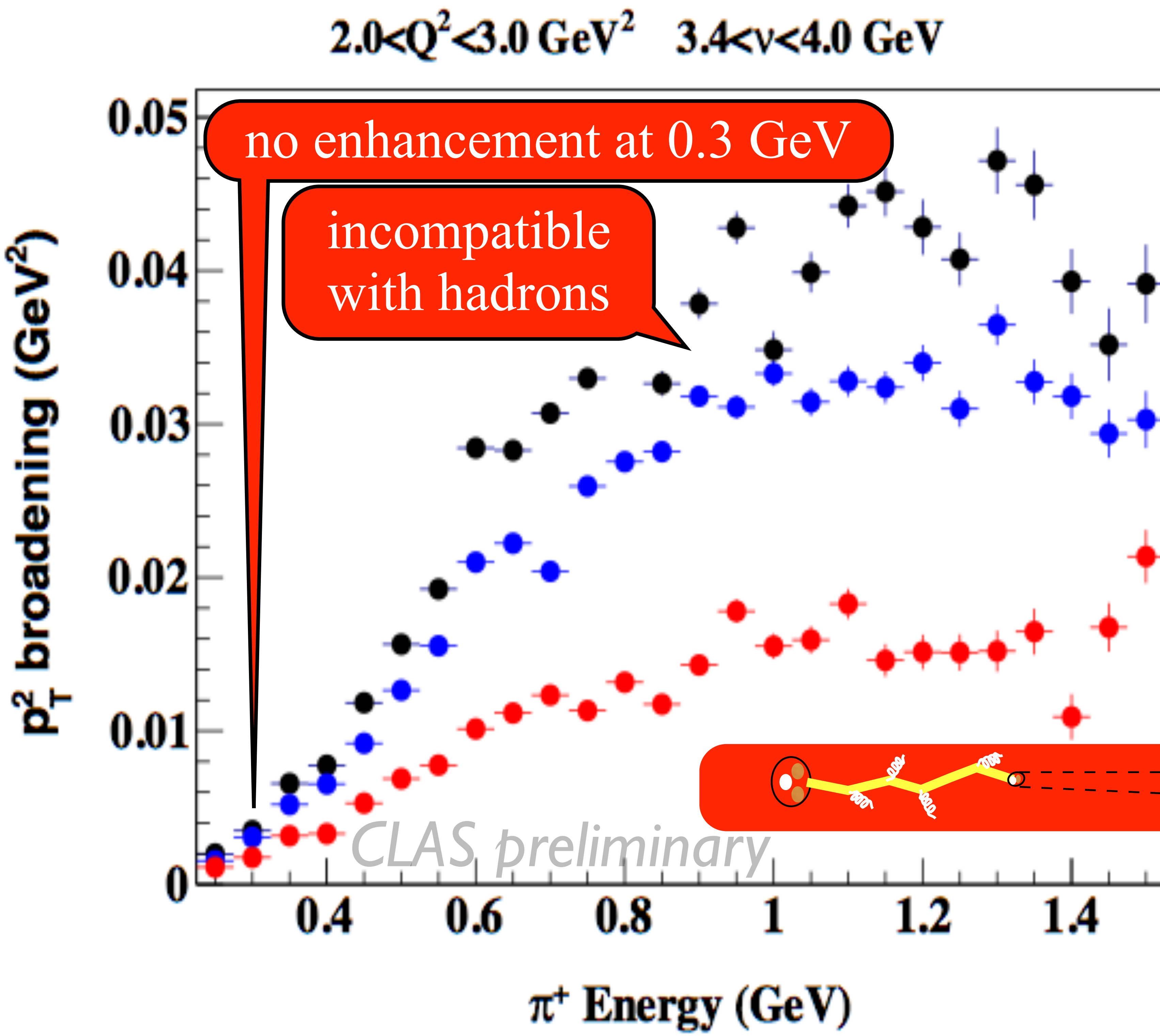
Hadronic broadening or partonic broadening?

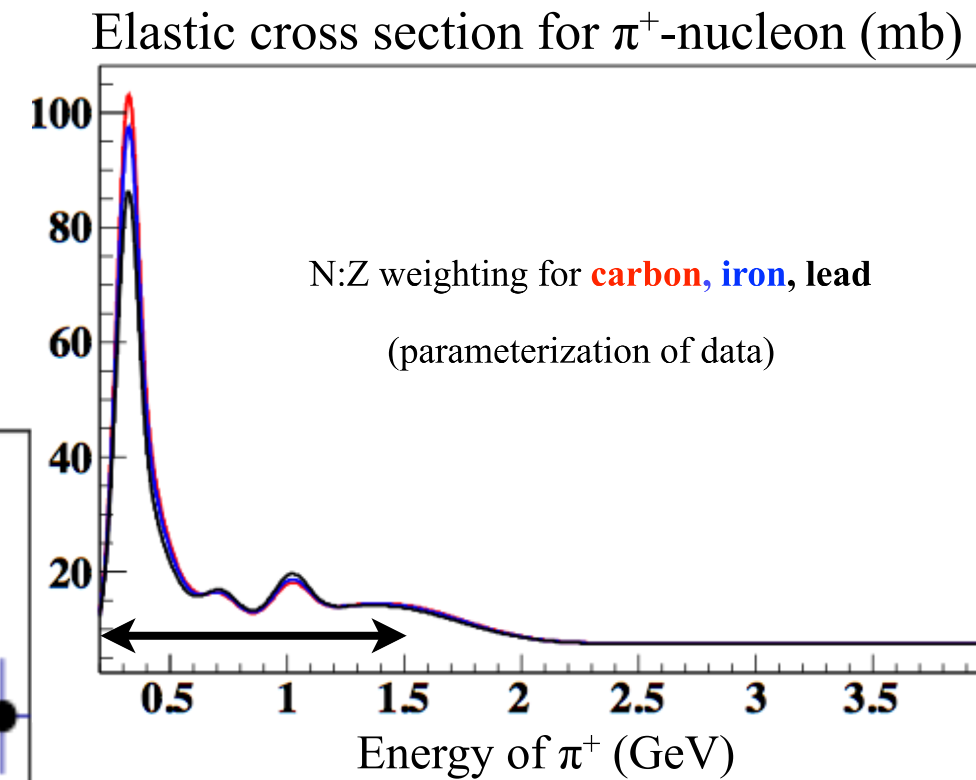


Elastic cross section for π^+-nucleon



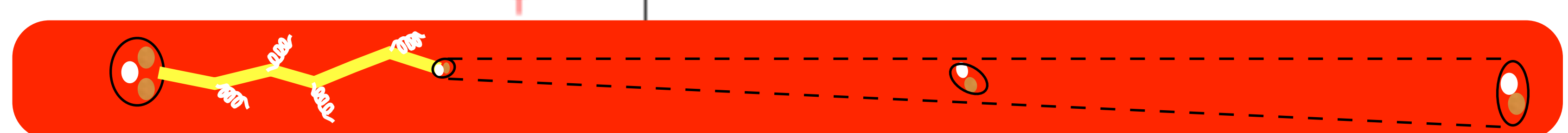
p_T^2 Broadening vs. Hadron Energy





No visible evidence of hadronic elastic scattering? Suggests:

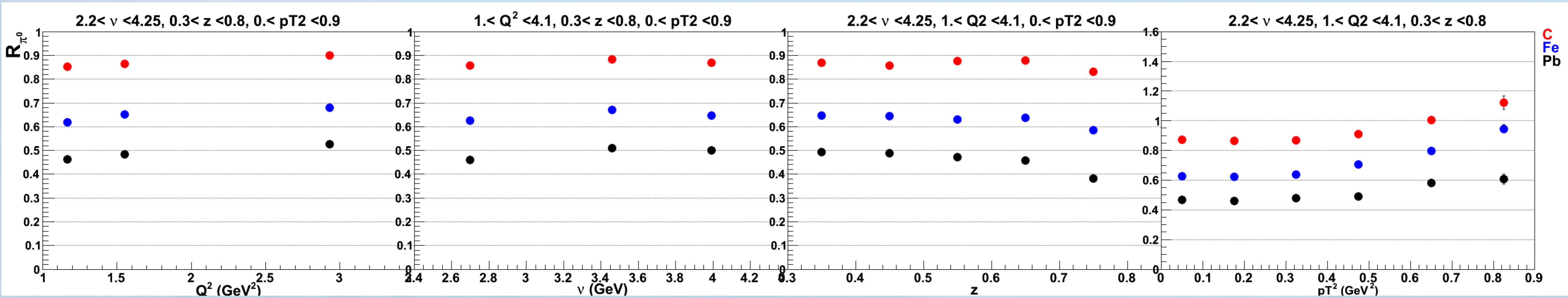
1) formation length is very long for these events



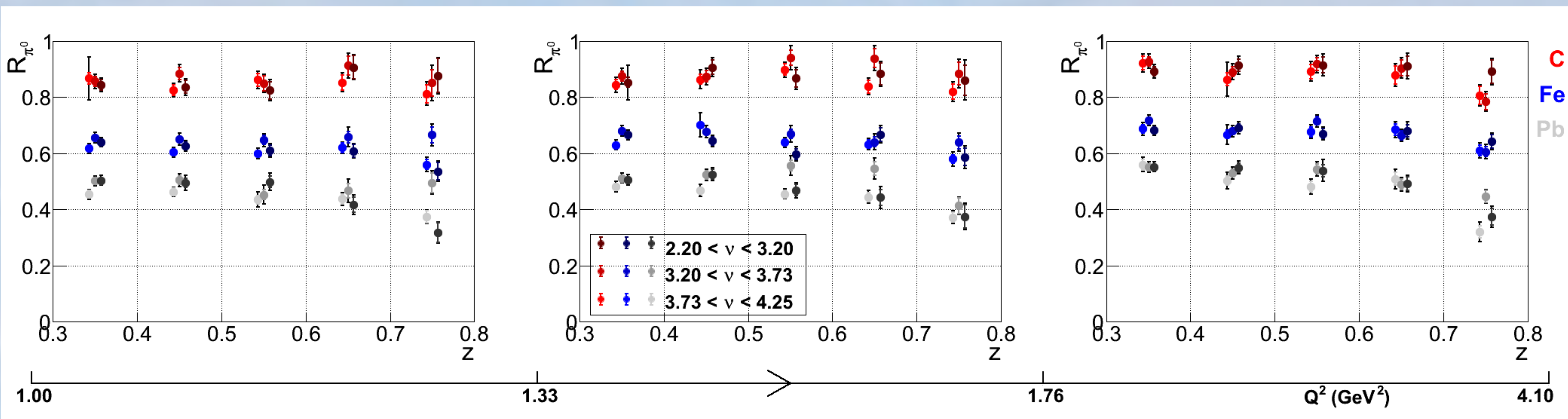
2) broadening is purely partonic

New π^0 hadron multiplicity ratios from CLAS

PhD thesis of Taisiya Mineeva



Integrated to 1 dimension

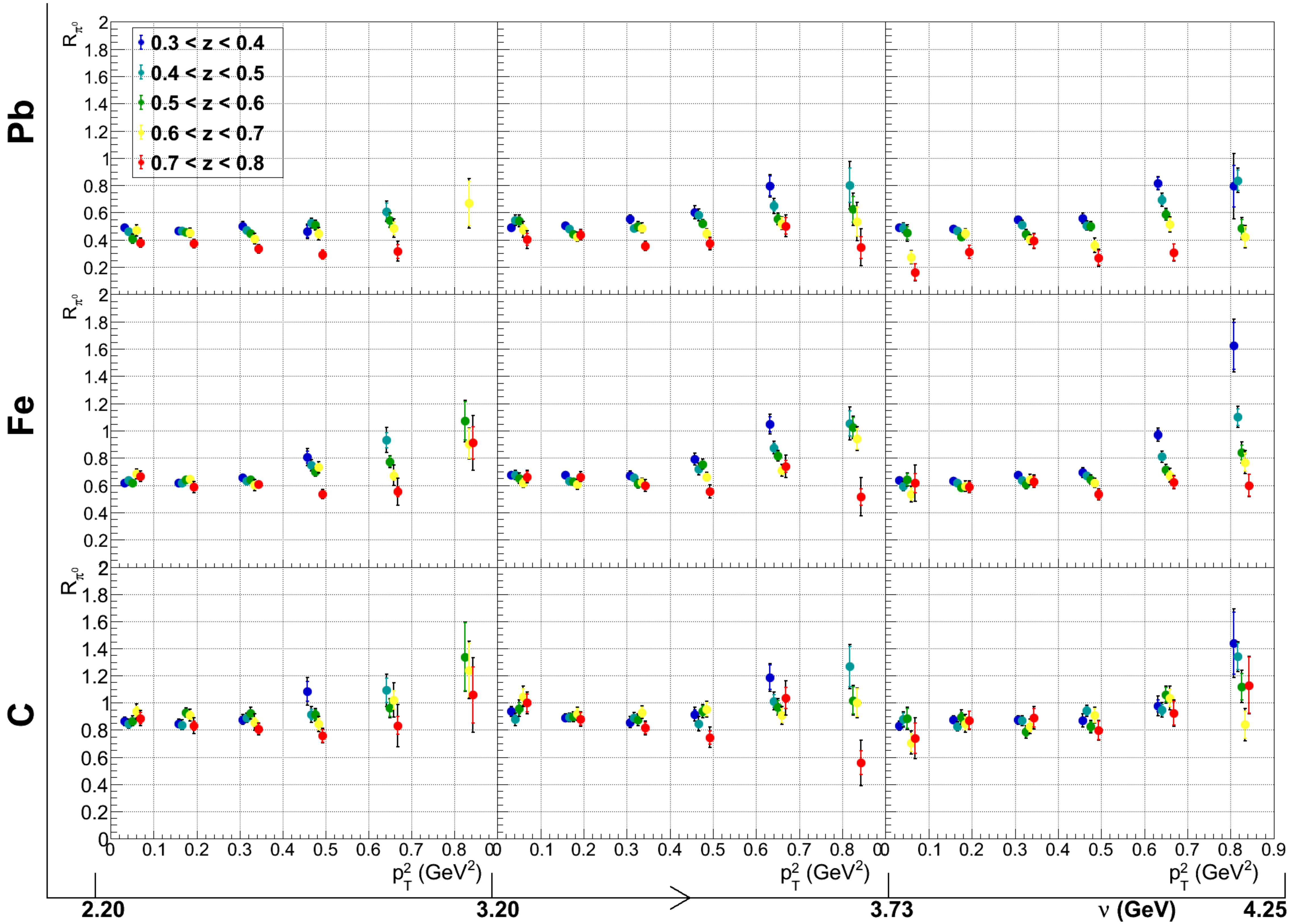


3-fold differential, z dependence vs. ν and Q^2

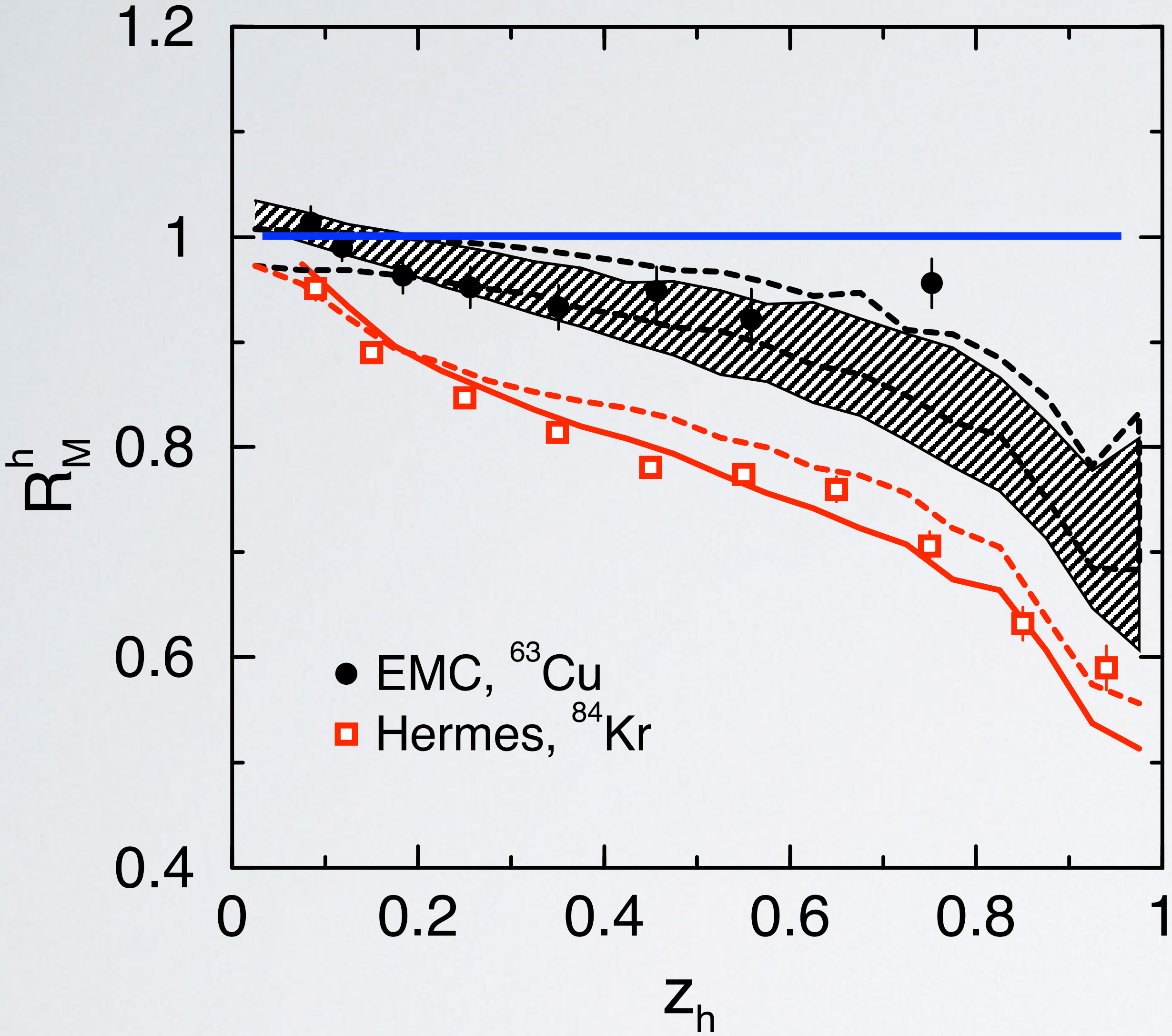
New π^0 hadron multiplicity ratios from CLAS, pg 2/2

PhD thesis of Taisiya Mineeva

3-fold differential, p_T dependence vs. ν and z



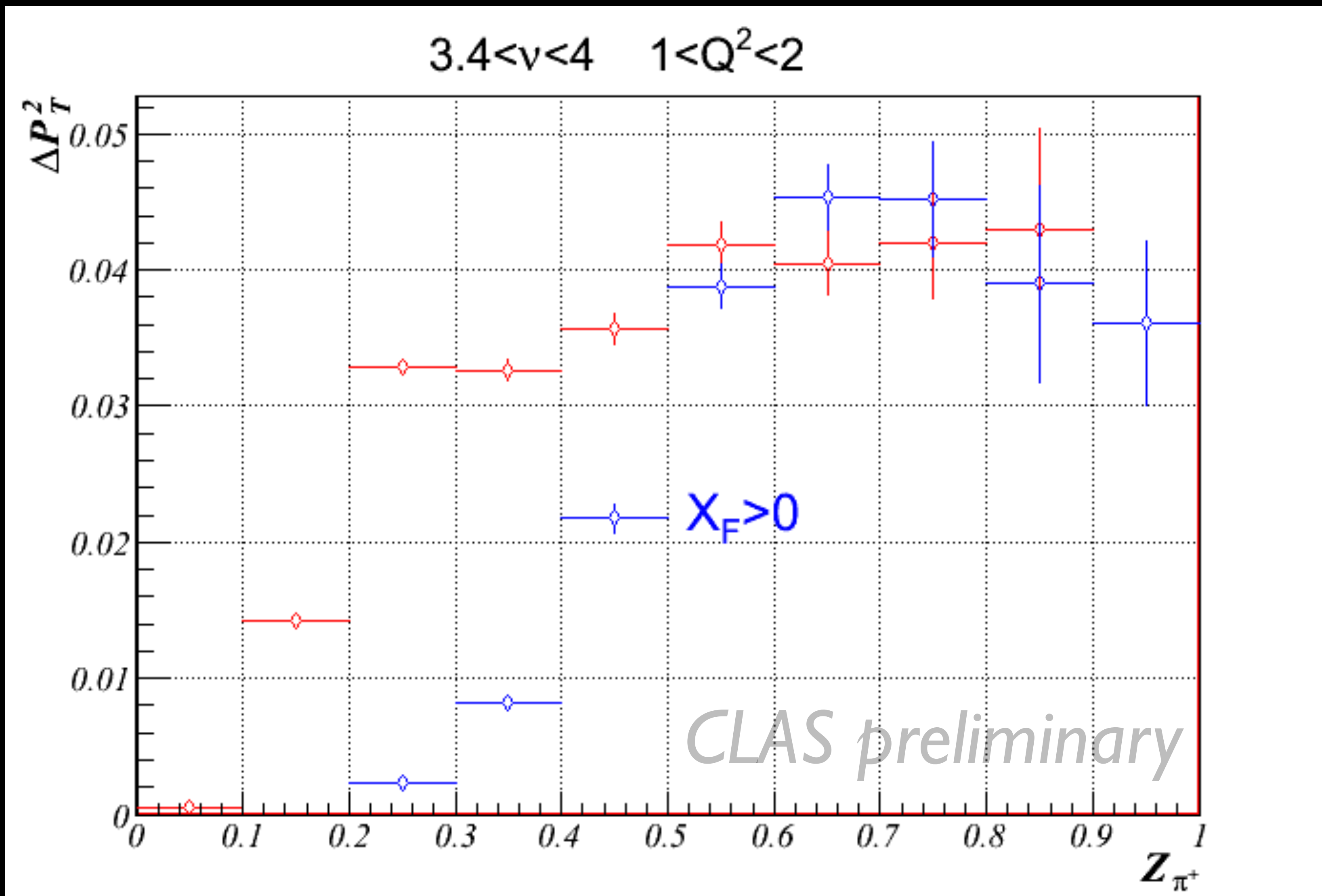
EMC DATA

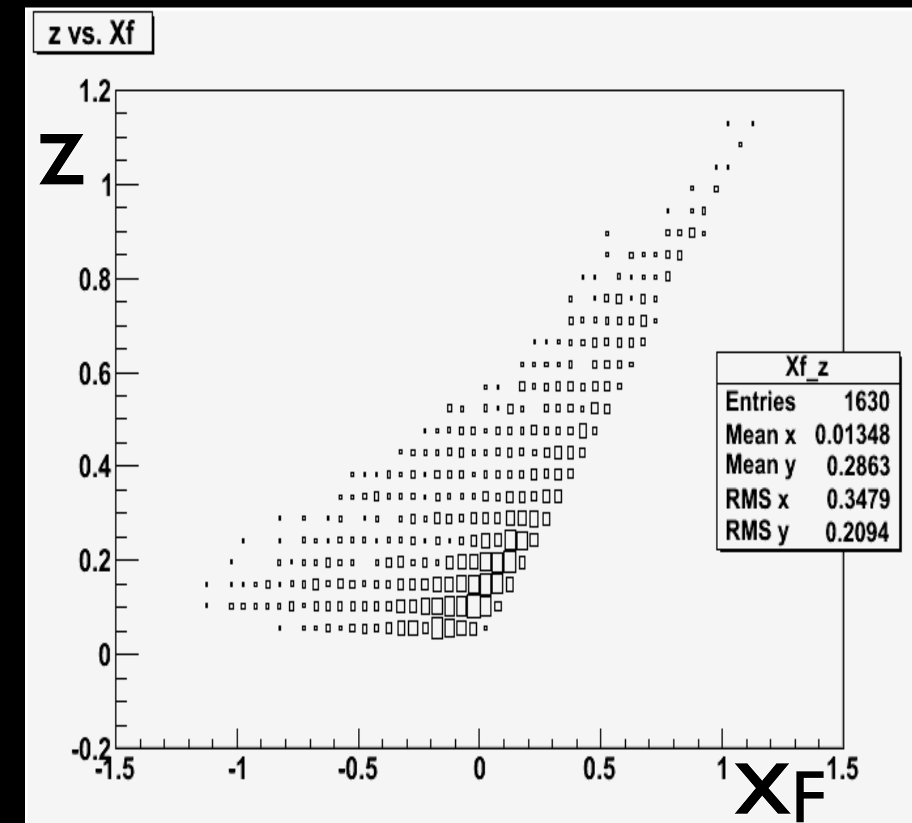


- HERMES (27 GeV) and EMC (100/280 GeV)
- Curves by Gallmeister and Mosel, nucl-th/0701064
- Note: radius $(Pb/Cu)^2 > 2$
- Note: data include protons, which were shown to “anti-attenuate” by HERMES

→ substantial attenuation expected at EIC for pions from Pb

New: dependence of p_T broadening on Feynman x

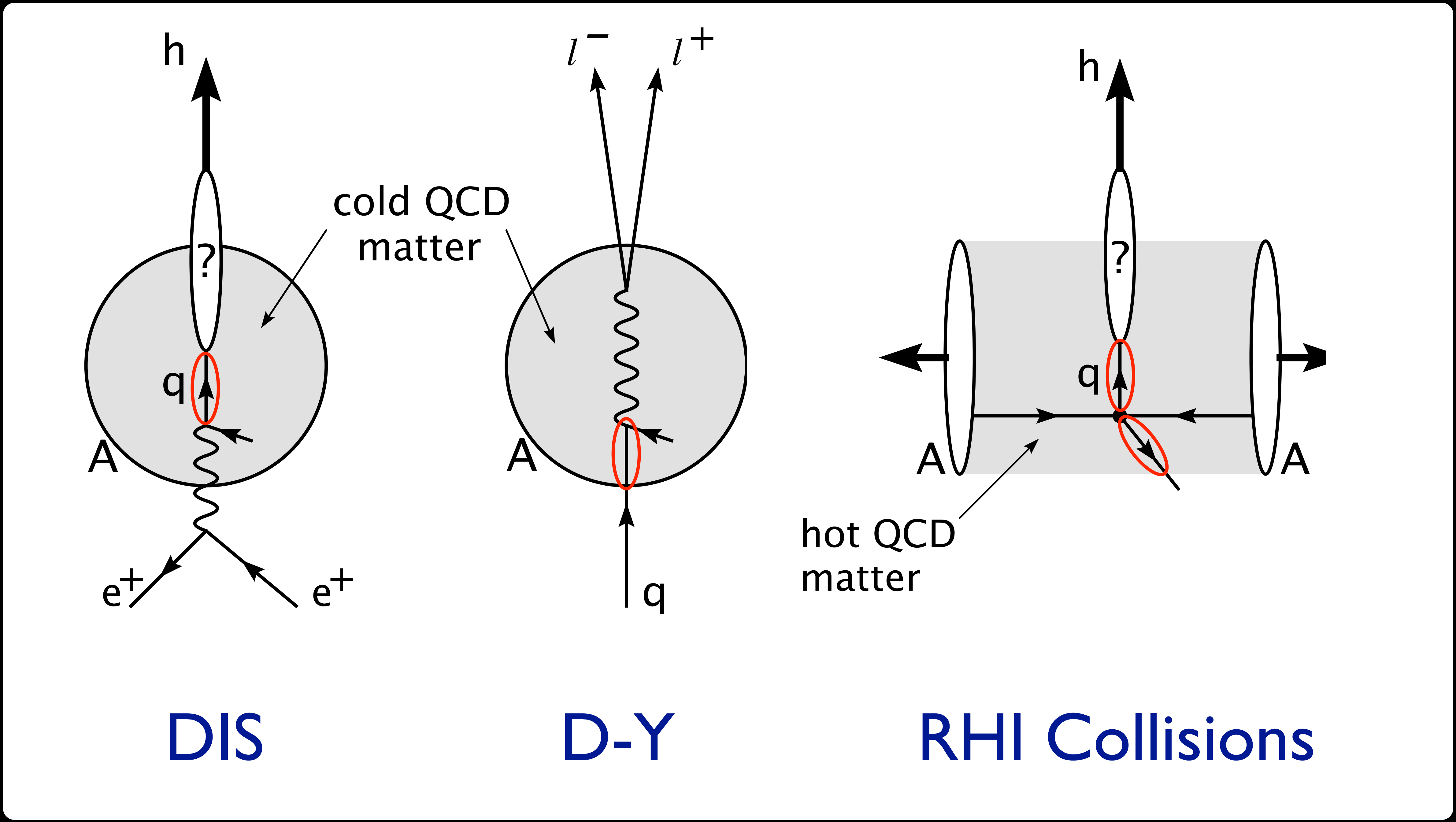




- x_F and z_h are partially correlated

- Feynman x is the fraction ${}^{\pi}p_L/\max\{{}^{\pi}p_L\}$ in the γ^*-N CM system
- Separate current ($x_F>0$) and target ($x_F<0$) fragmentation
- First observation that *p_T broadening originates in both regimes*

Comparison of Parton Propagation in Three Processes



Experiments

- SLAC: 20 GeV e^--beam on Be, C, Cu Sn, PRL 40 (1978) 1624
- EMC: 100-200 GeV μ-beam on Cu, Z.Phys. C52 (1991) 1.
- WA21/59: 4-64 GeV ν-beam on Ne, Z.Phys. C70 (1996) 47.
- E665: Fermilab, slow protons in μ-beam on Xe (1990's)
- Drell-Yan: Fermilab E772, E866, 1990's
- HERMES: 27.6 GeV e+(e-) on He, N, Ne, Kr, Xe; five pub's
- CLAS: 5 GeV e^--beam on C, Fe, Pb
- FNAL E906 Drell-Yan at 120 GeV (in progress)
- JLAB12(near future): 11 GeV e^- (CLAS12)
- EIC(future)
- RHIC
- LHC Pb-Pb, p-Pb